A challenge to the standard cosmological model

Subir Sarkar

In the ΛCDM cosmological model the universe is assumed to be statistically isotropic & homogeneous when averaged on large scales. That the CMB has a dipole anisotropy is supposedly due to our peculiar (non-Hubble) motion because of local inhomogeneity. There should then be a similar dipole in the sky distribution of high redshift sources. Using catalogues of radio sources & quasars we find that this standard expectation is rejected at $>5\sigma$. This under-mines the standard practice of boosting to the 'CMB frame' to analyse cosmological data, in particular to infer an isotropic acceleration of the Hubble expansion rate which is then interpreted as due to a Cosmological Constant.

Celebrating the 70th birthdays of Werner Hofmann & Felix Aharonian, MPIK Heidelberg, 8 Dec 2022

INFERENCE

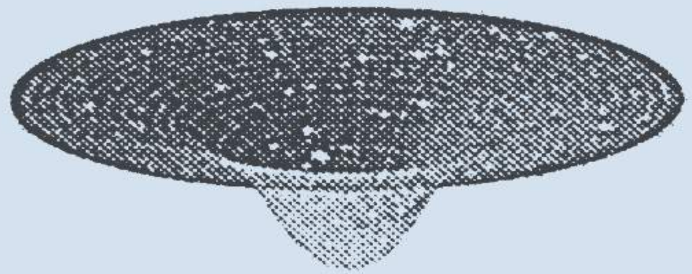
SEARCH

PHYSICS / CRITICAL ESSAY

VOL. 6, NO. 4 / **MARCH 2022**

Heart of Darkness

Subir Sarkar



Cosmologists are often in error, but never in doubt.
—Lev Landau[1]

IN THE STANDARD MODEL of cosmology, about seventy percent of the energy density of the universe—the dark energy driving its accelerating rate of expansion—is described by Albert Einstein's cosmological constant.[2] In this essay, I argue that the standard model of cosmology is wrong. This should come as no surprise. "The history of science," Georges Lemaître remarked, "provides many instances of discoveries which have been made for reasons which are no longer considered satisfactory." It may be, he added suggestively, "that the discovery of the cosmological constant is such a case."[3]

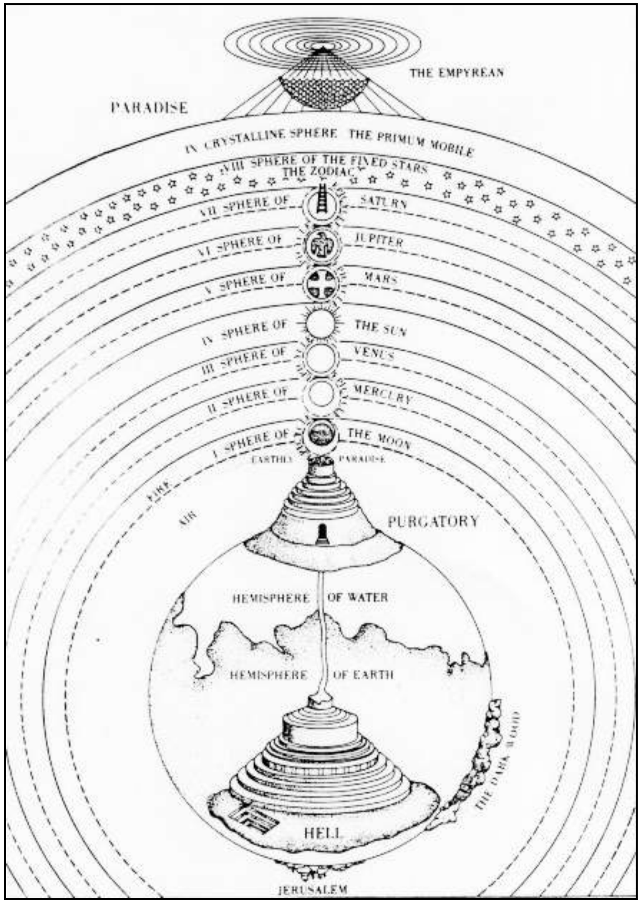
Subir Sarkar is Emeritus Professor at the Rudolf Peierls Centre for Theoretical Physics, University of Oxford.

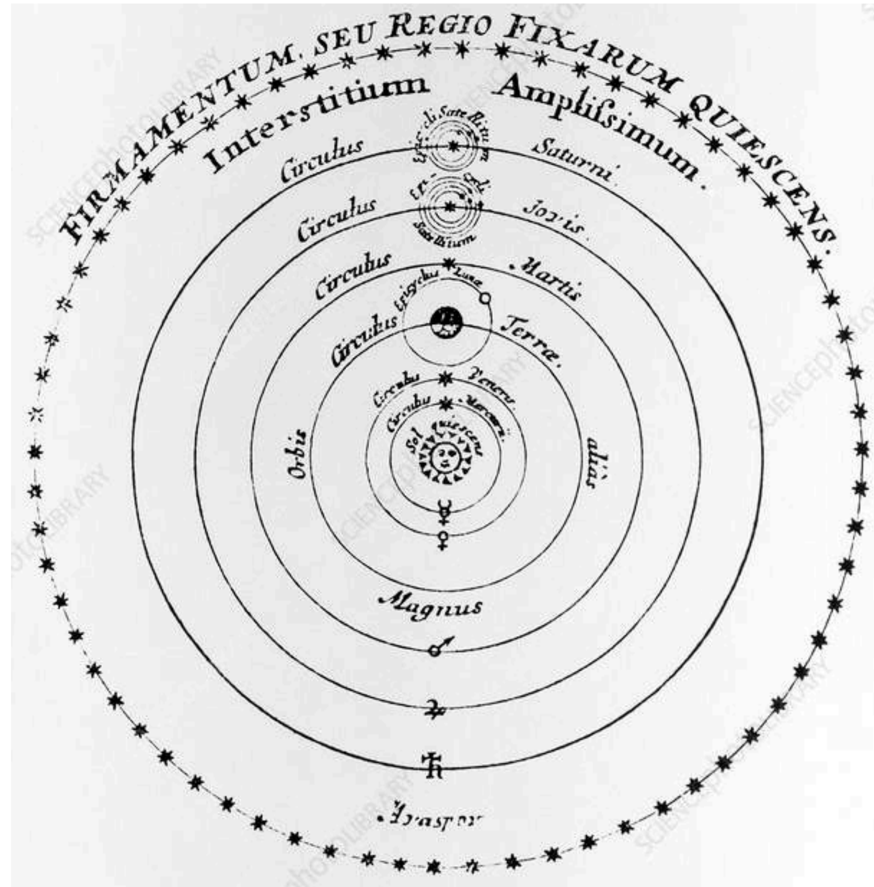
https://doi.org/10.37282/991819.22.21

The 'standard cosmology' in Europe which lasted ~2000 yr was *simple* and gave a *good* fit to all available data

it yielded to the heliocentric Universe, wherein the Earth was demoted from being at its very centre ... the Sun took its place

Aristotle ... Ptolemy → The Divine Comedy, Dante Alligheri (1321)

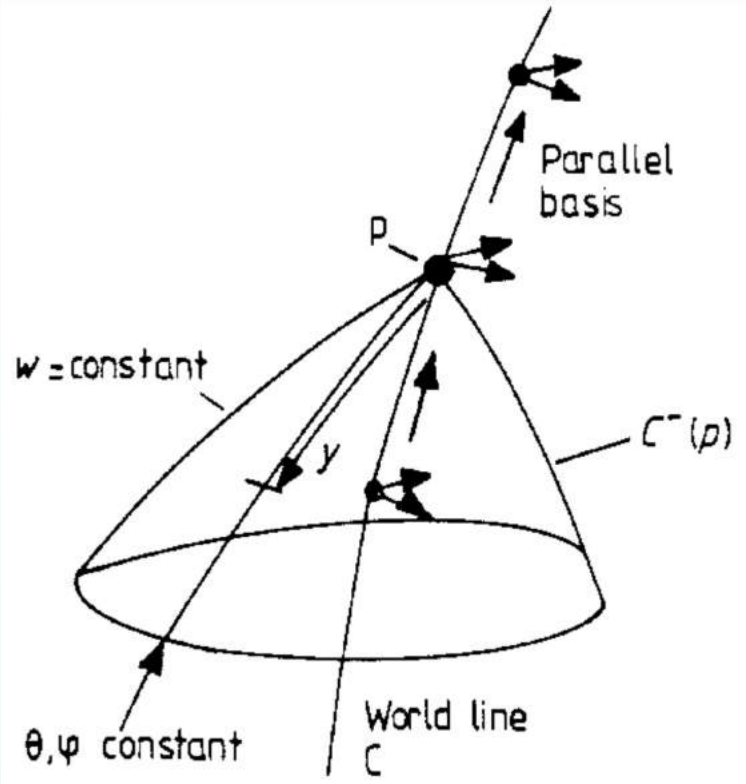




Nicholas Copernicus, *De revolutionibus orbium coelestium* (1543)

Four centuries later when the first relativistic cosmological models were constructed (Einstein 1917, Friedmann 1921, Lemaître 1927), this 'Copernican Principle' was extended further to demote the Sun too, from being at the centre of the Universe …

All we can 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)

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 STEADY-STATE THEORY OF THE EXPANDING UNIVERSE

H. Bondi and T. Gold

(Received 1948 July 14)

Summary

The applicability of the laws of terrestrial physics to cosmology is examined critically. It is found that terrestrial physics can be used unambiguously only in a stationary homogeneous universe. Therefore a strict logical basis for cosmology exists only in such a universe. The implications of assuming these properties are investigated.

Considerations of local thermodynamics show as clearly as astronomical observations that the universe must be expanding. Hence, there must be continuous creation of matter in space at a rate which is, however, far too low for direct observation. The observable properties of such an expanding stationary homogeneous universe are obtained, and all the observational tests are found to give good agreement.

The physical properties of the creation process are considered in some detail, and the possible formulation of a field theory is critically discussed.

---

1. *The perfect cosmological principle*

The 'Perfect' version was abandoned following the discovery of the CMB in 1965 and the realization that the universe *does* have a beginning ...

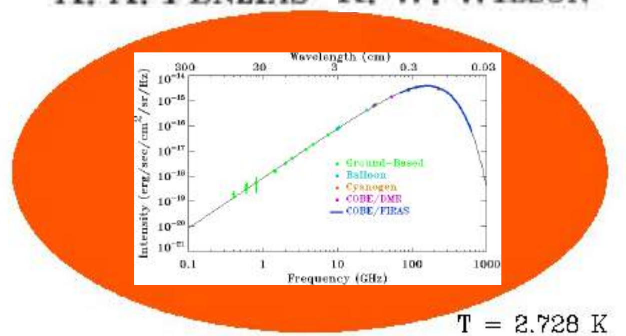
A MEASUREMENT OF EXCESS ANTENNA TEMPERATURE AT 4080 Mc/s

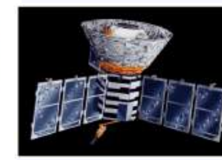
Measurements of the effective zenith noise temperature of the 20-foot horn-reflector antenna (Crawford, Hogg, and Hunt 1961) at the Crawford Hill Laboratory, Holmdel, New Jersey, at 4080 Mc/s have yielded a value about 3.5° K higher than expected. This excess temperature is, within the limits of our observations, isotropic, unpolarized, and free from seasonal variations (July, 1964–April, 1965). A possible explanation for the observed excess noise temperature is the one given by Dicke, Peebles, Roll, and Wilkinson (1965) in a companion letter in this issue.

A. A. Penzias R. W. Wilson

May 13, 1965

Bell Telephone Laboratories, Inc
Crawford Hill, Holmdel, New Jersey





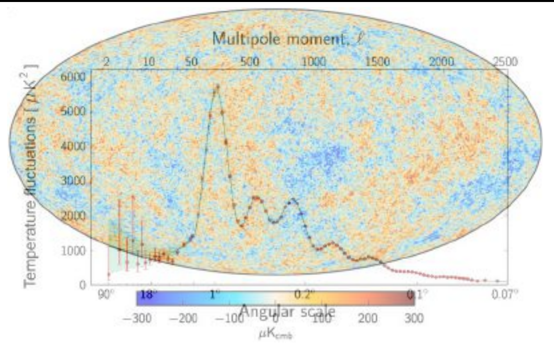
But the (spatial) cosmological principle lived on!

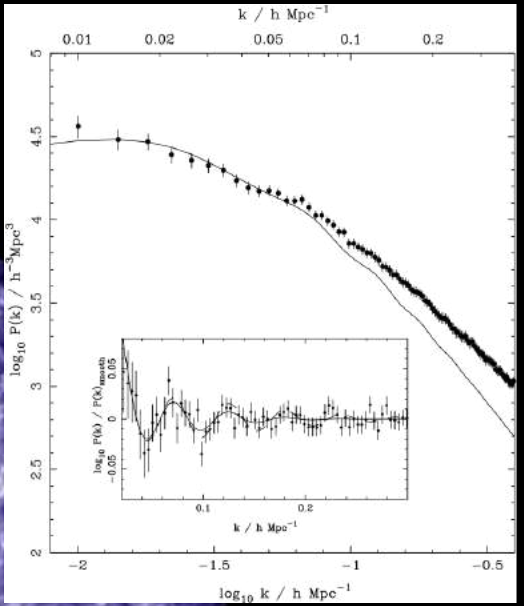
The real reason, though, for our adherence here to the Cosmological Principle is not that it is surely correct, but rather, that it allows us to make use of the extremely limited data provided to cosmology by observational astronomy. ...

... 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)

This remains the *key* assumption of the standard cosmological model:





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

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

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

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

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

$$\Rightarrow H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G_{\text{N}}\rho_{\text{m}}}{3} - \frac{k}{a^2} + \frac{\Lambda}{3}$$
$$\equiv H_0{}^2\left[\Omega_{\text{m}}(1+z)^3 + \Omega_k(1+z)^2 + \Omega_\Lambda\right]$$

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

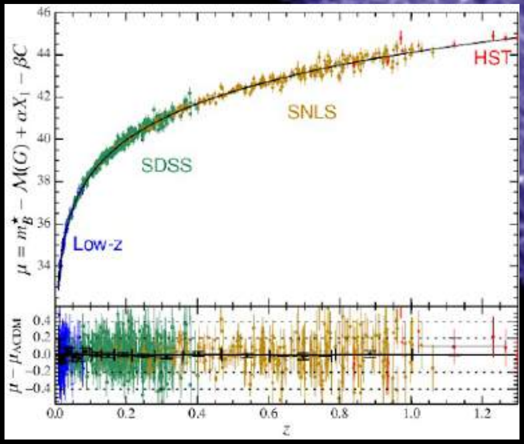
$$\ddot{a} = -\frac{4\pi G}{3}(\rho + 3P)\,a$$

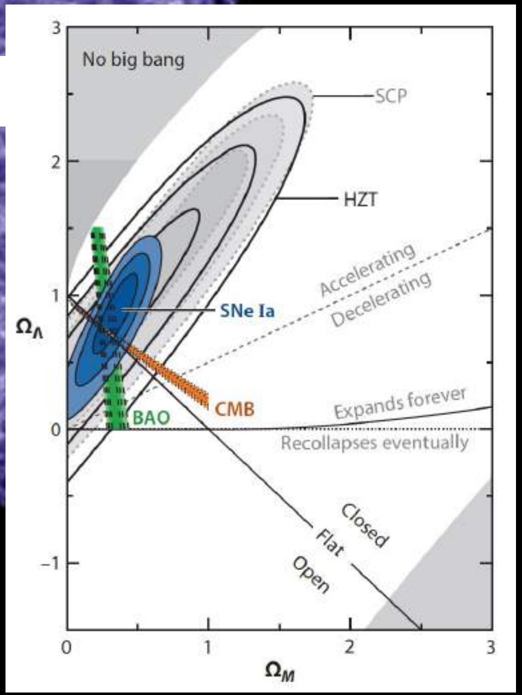
$$\mathbf{\Omega_m + \Omega_k + \Omega_\Lambda = 1}$$

$0.8\Omega_{\text{m}} - 0.6\Omega_\Lambda \approx -0.2$ (SNe Ia),
$\Omega_{\text{k}} \approx 0.0$ (CMB), $\Omega_{\text{m}} \sim 0.3$ (Clusters, BAO)

$\Omega_\Lambda = 1 - \Omega_{\text{m}} - \Omega_{\text{k}} \sim 0.7 \Rightarrow \boldsymbol{\Lambda \sim 2H_0{}^2}$

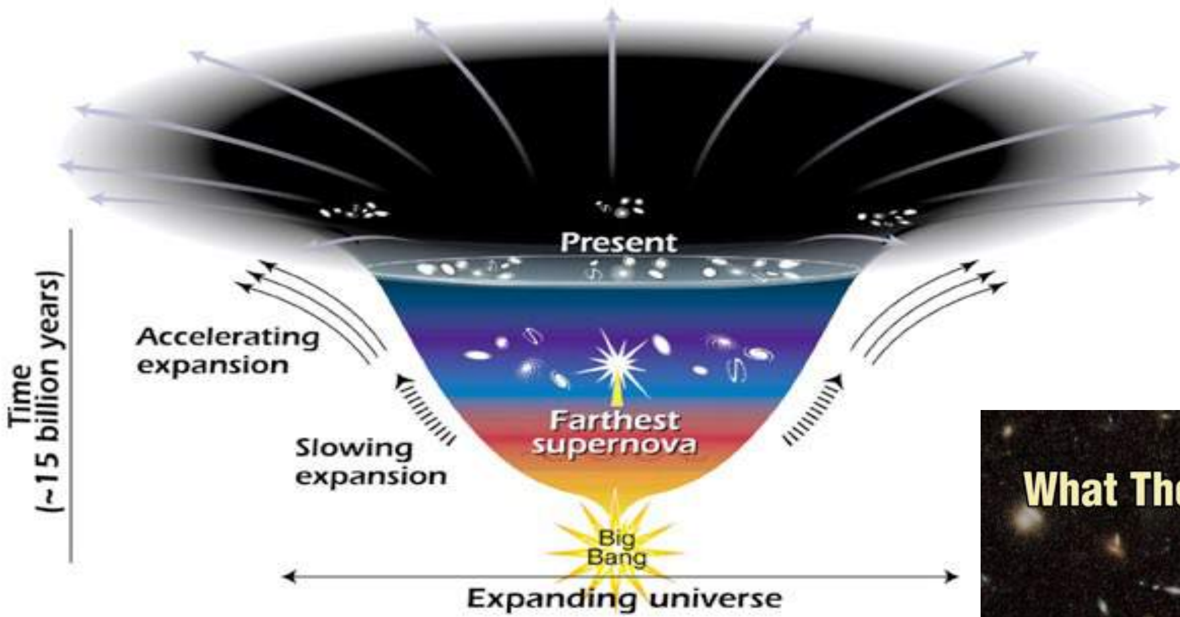
$(\rho_\Lambda)^{1/4} = (2H_0{}^2/8\pi G_{\text{N}})^{1/4} \sim 10^{-12}$ GeV



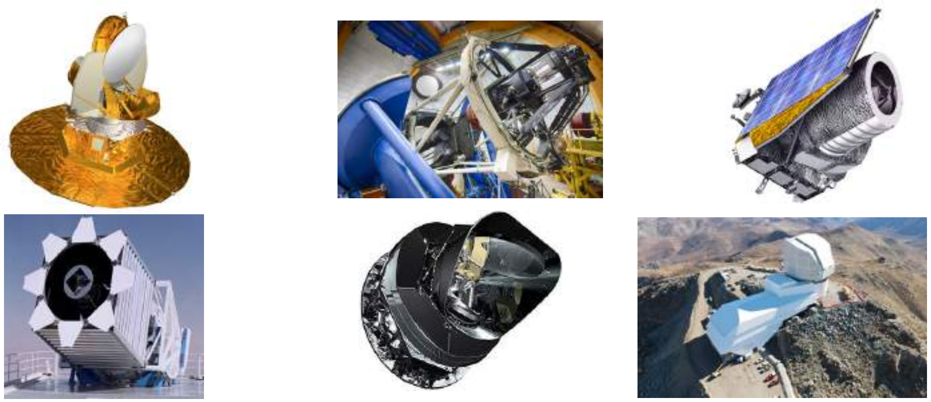


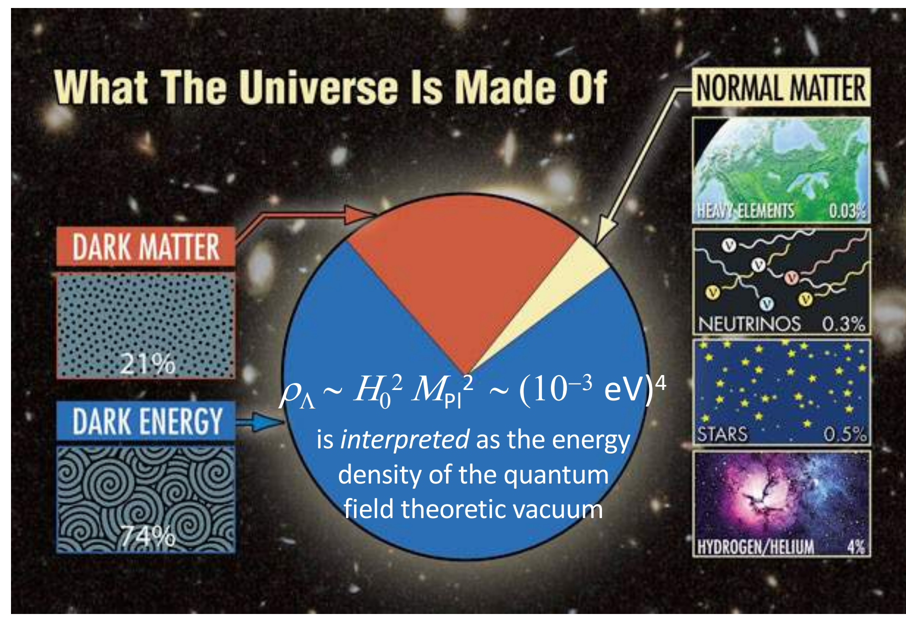
THE COSMIC SUM RULE IS USED TO *INFER* THAT Λ IS OF ORDER H_0^2 FROM OBSERVATIONS OF SNe Ia, CMB, BAO, LENSING ETC

(THERE IS AS YET NO COMPELLING *DYNAMICAL* EVIDENCE FOR Λ)



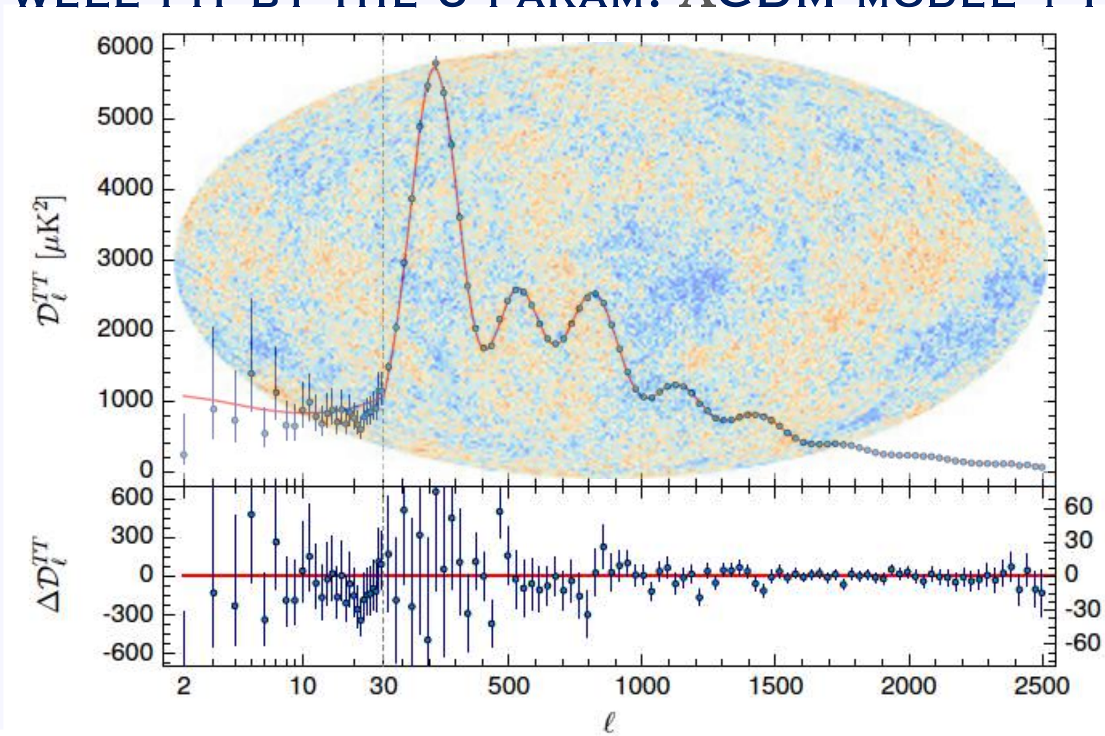
The ΛCDM model is 'simple' (if we take Λ to be just another parameter!) and fits the data (with just a few anomalies) … but lacks a *physical* foundation





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***

CMB data is well-fit by the 6-param. ΛCDM model + power-law *P*(*k*)



Planck collab., A&A **594**:A13,2016

Parameter	[1] *Planck* TT+lowP	[2] *Planck* TE+lowP	[3] *Planck* EE+lowP	[4] *Planck* TT,TE,EE+lowP
$\Omega_b h^2$	0.02222 ± 0.00023	0.02228 ± 0.00025	0.0240 ± 0.0013	0.02225 ± 0.00016
$\Omega_c h^2$	0.1197 ± 0.0022	0.1187 ± 0.0021	$0.1150^{+0.0048}_{-0.0055}$	0.1198 ± 0.0015
$100\theta_{MC}$	1.04085 ± 0.00047	1.04094 ± 0.00051	1.03988 ± 0.00094	1.04077 ± 0.00032
τ	0.078 ± 0.019	0.053 ± 0.019	$0.059^{+0.022}_{-0.019}$	0.079 ± 0.017
$\ln(10^{10}A_s)$	3.089 ± 0.036	3.031 ± 0.041	$3.066^{+0.046}_{-0.041}$	3.094 ± 0.034
n_s	0.9655 ± 0.0062	0.965 ± 0.012	0.973 ± 0.016	0.9645 ± 0.0049
H_0	67.31 ± 0.96	67.73 ± 0.92	70.2 ± 3.0	67.27 ± 0.66
Ω_m	0.315 ± 0.013	0.300 ± 0.012	$0.286^{+0.027}_{-0.038}$	0.3156 ± 0.0091
σ_8	0.829 ± 0.014	0.802 ± 0.018	0.796 ± 0.024	0.831 ± 0.013
$10^9 A_s e^{-2\tau}$	1.880 ± 0.014	1.865 ± 0.019	1.907 ± 0.027	1.882 ± 0.012

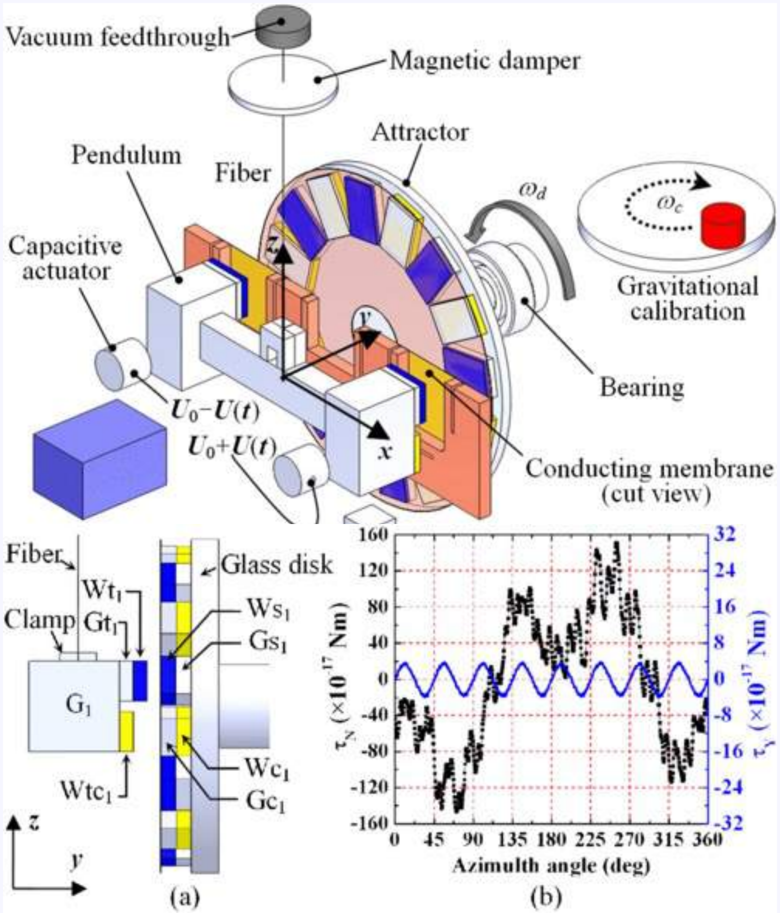
There is no entry for Λ!

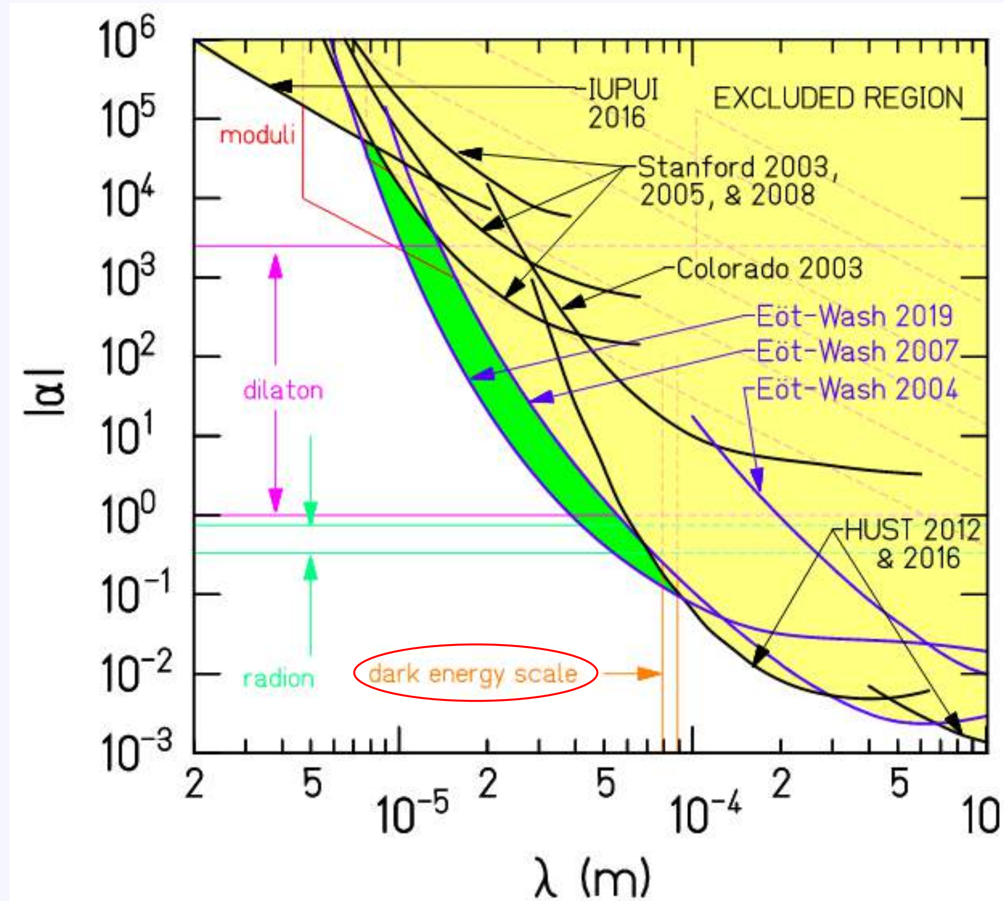
There is no *direct* sensitivity of CMB anisotropy to dark energy … it is all *inferred* (using $\Omega_m + \Omega_k + \Omega_\Lambda \equiv 1$)

(To directly detect Λ using late-ISW correlations between CMB & structure will require ~**10** million redshifts)

NB: There is *no* evidence for any change in the inverse-square law of gravitation at the inferred **'dark energy' scale** of ~ **10^{-3} eV**: $\rho_\Lambda^{-1/4} \sim (H_0/\sqrt{G_N})^{-1/2} \sim$ **0.1 mm**

$$V(r) = -G\frac{m_1 m_2}{r}[1 + \alpha \exp(-r/\lambda)]$$



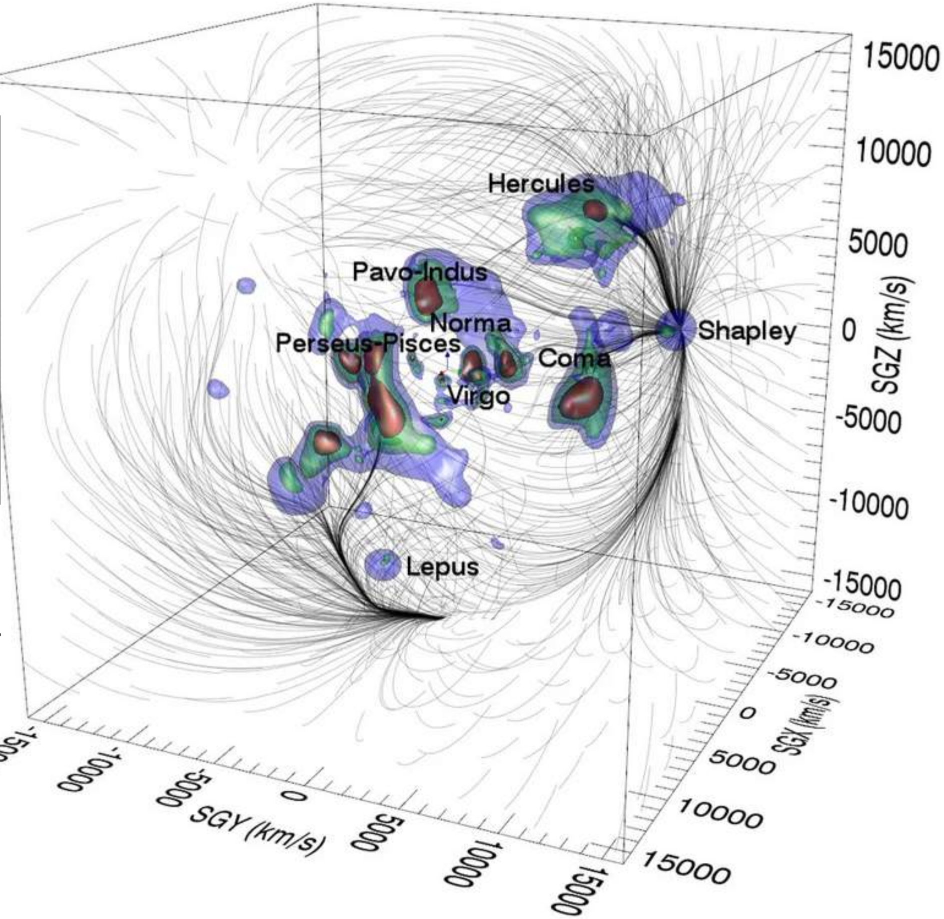


Lee *et al*, PRL **124**:101101,2020

… or for any proposed 'screening' mechanisms,
e.g. chameleon and symmetron theories of modified gravity

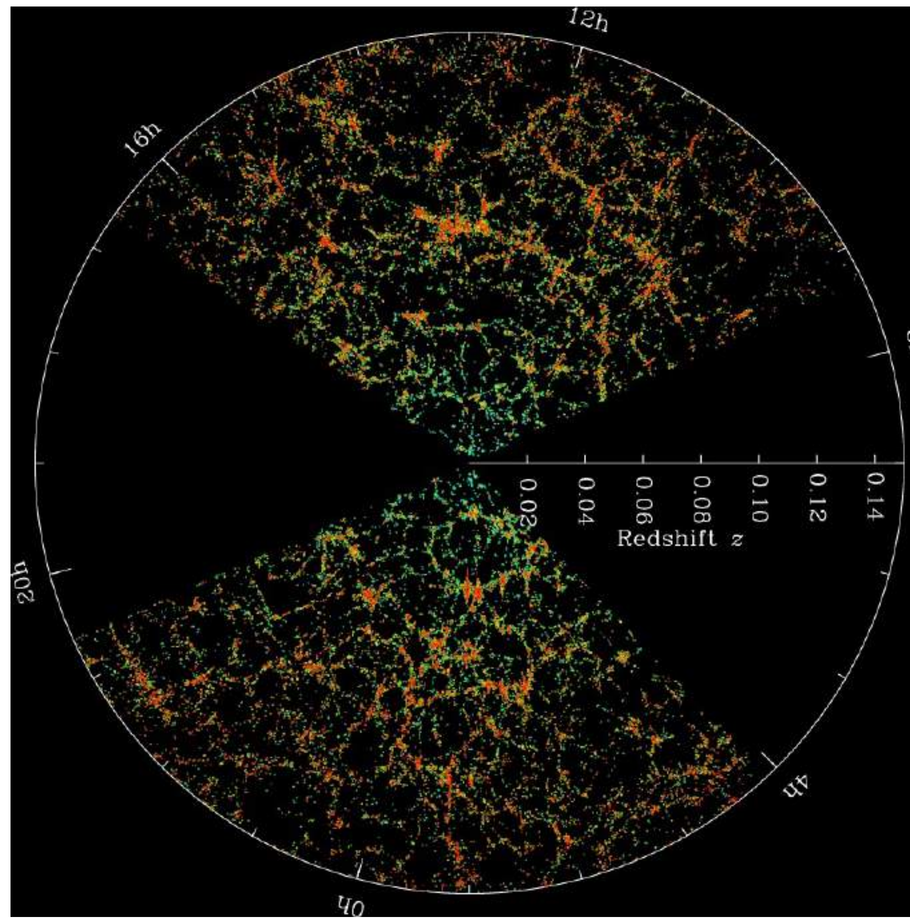
How well does the real universe conform to the standard FLRW model description?

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

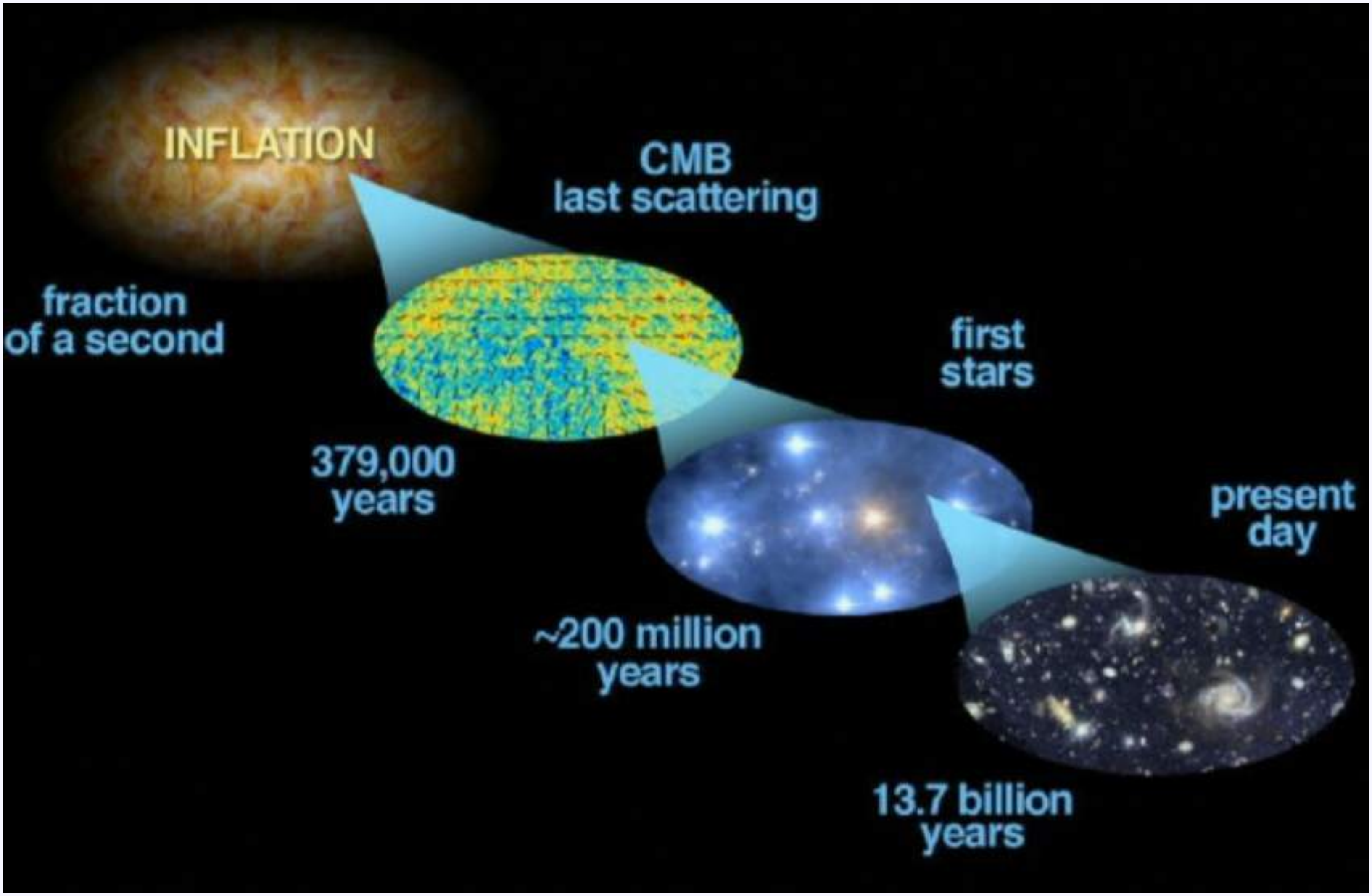


Is it justified to approximate it as *exactly* homogeneous?

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

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

The growth of structure is well-explained by ΛCDM + standard model of structure formation

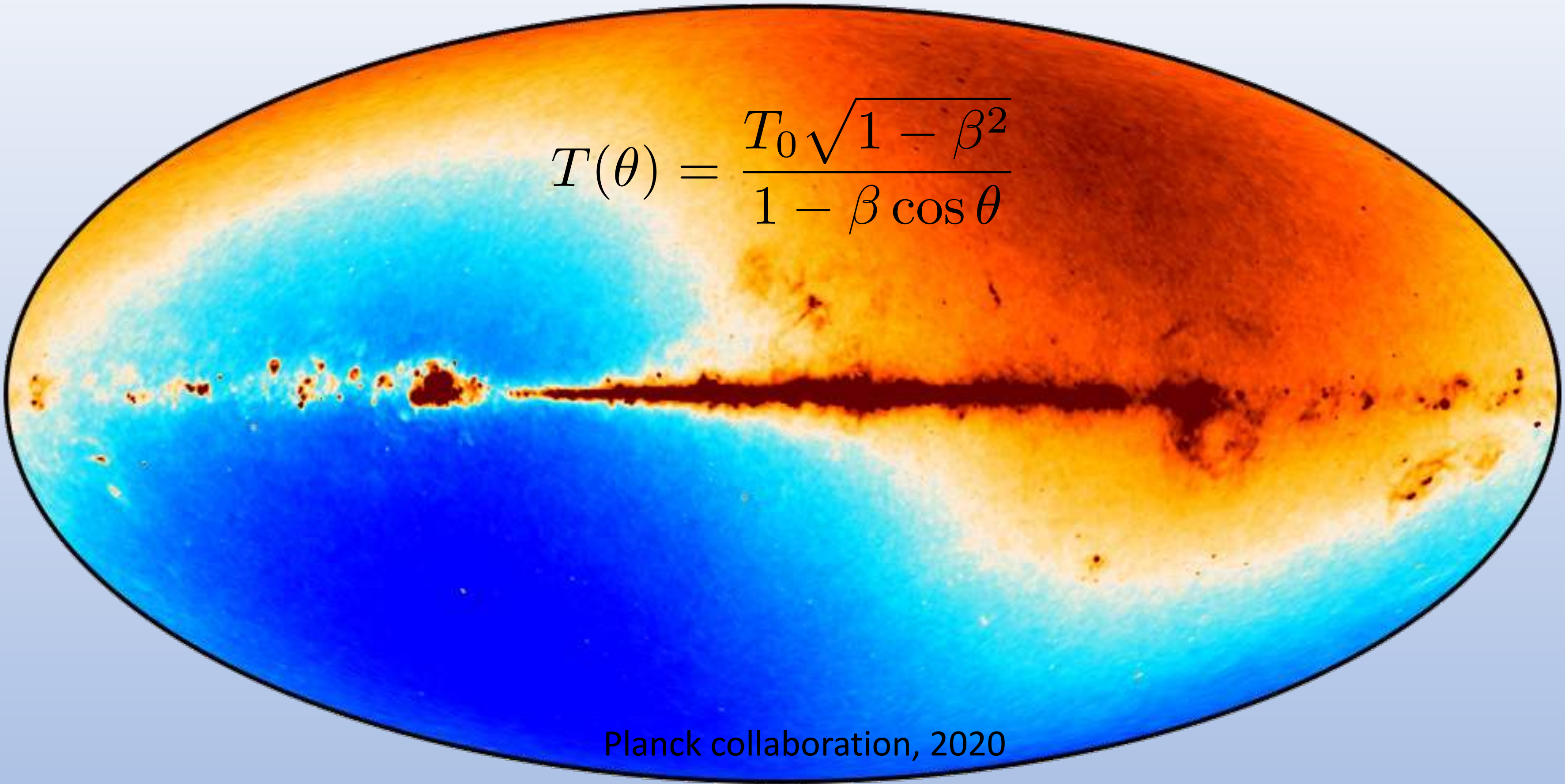


Courtesey: NASA

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 IS *NOT* ISOTROPIC AS OBSERVED BY US

There is a dipole with $\Delta T/T \sim 10^{-3}$ … 100 times *bigger* than the small-scale fluctuations



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

Planck collaboration, 2020

Sciama 1967, Peebles & Wilkinson 1968

This is *interpreted* as due to our motion at 370 km/s wrt the 'cosmic rest frame' in which the CMB is truly isotropic … and where the F-L equations are valid (if at all)

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 ~100/*h* Mpc

(Counts of galaxies in e.g. SDSS & WiggleZ surveys are said to scale as r^3 on larger scales)

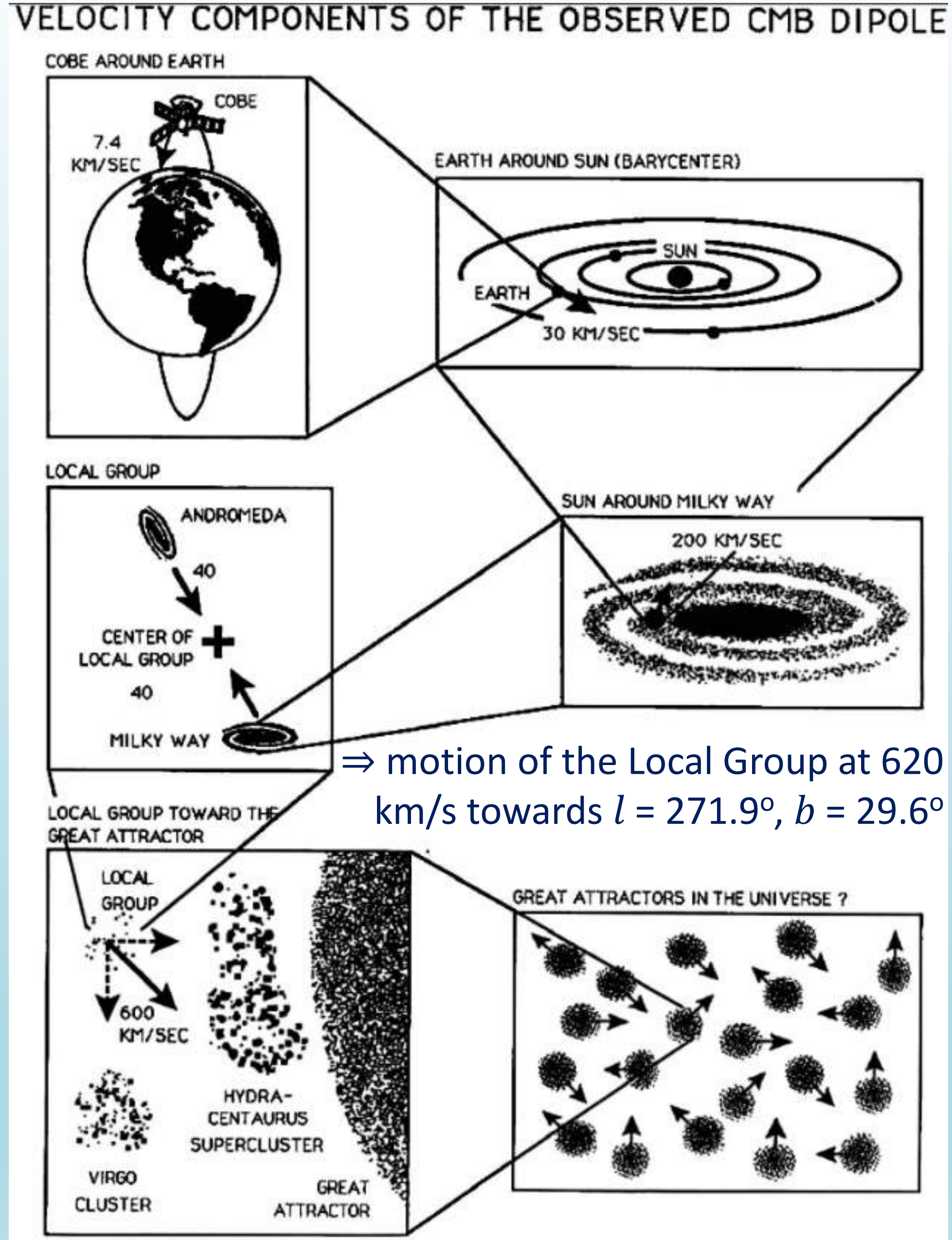
Peculiar Velocity of the Sun and its Relation to the Cosmic Microwave Background

NATURE **216**:748,1967

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.

The predicted CMB dipole was found – but we have *not* yet seen convergence to the 'CMB frame' … even out to ~300/*h* Mpc

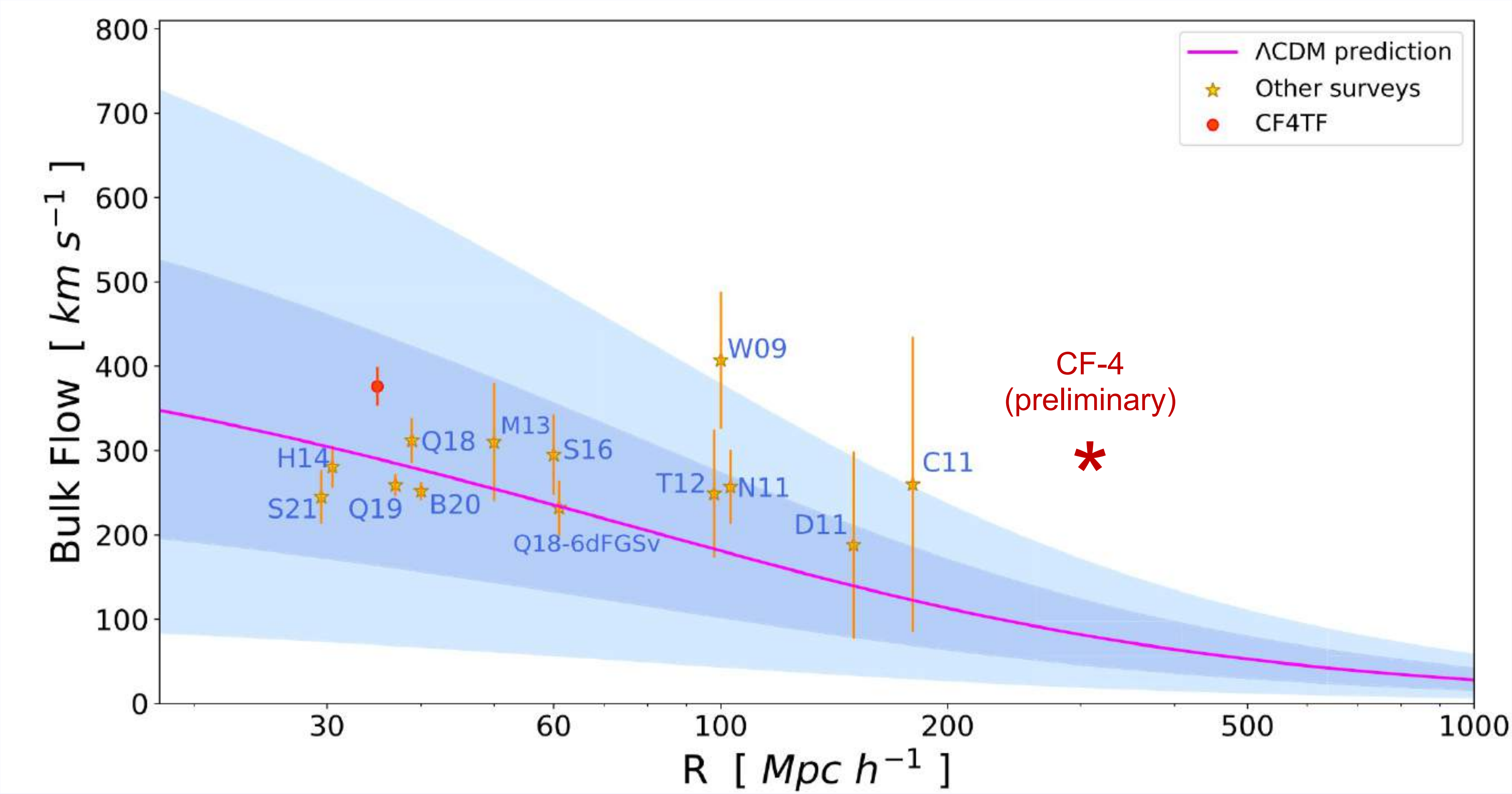


⇒ motion of the Local Group at 620 km/s towards l = 271.9°, b = 29.6°

Nevertheless data is 'corrected' by transforming to the CMB frame - in which FLRW *ought* to hold

George Smoot, Nobel Lecture, 8 Dec 2006

CONVERGENCE TO THE 'CMB FRAME' IS NOT SEEN EVEN OUT TO ~300h^{-1} 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'), <1% (0.1%) 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)

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

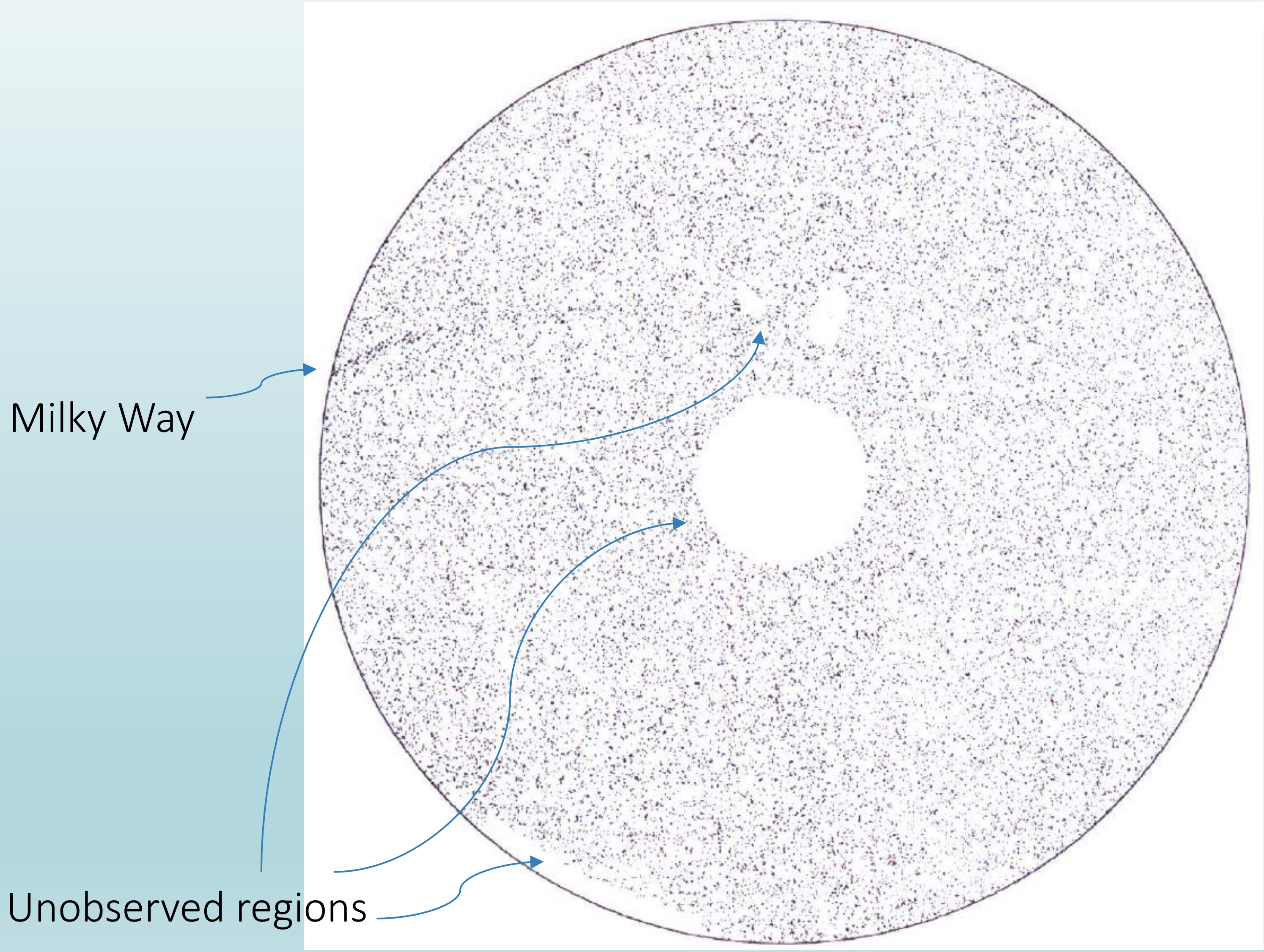
(a) the idea that the radio sources are at cosmological distances, or

(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.

Textbooks say that the distribution of distant radio sources demonstrates the isotropy of the Universe



Peebles, *Principles of Physical Cosmology*, 1993

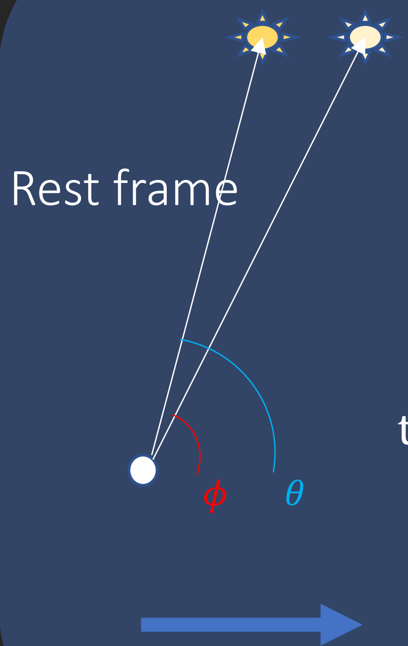
But if we are moving w.r.t. the cosmic rest frame, then distant sources *cannot* be isotropic!

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)

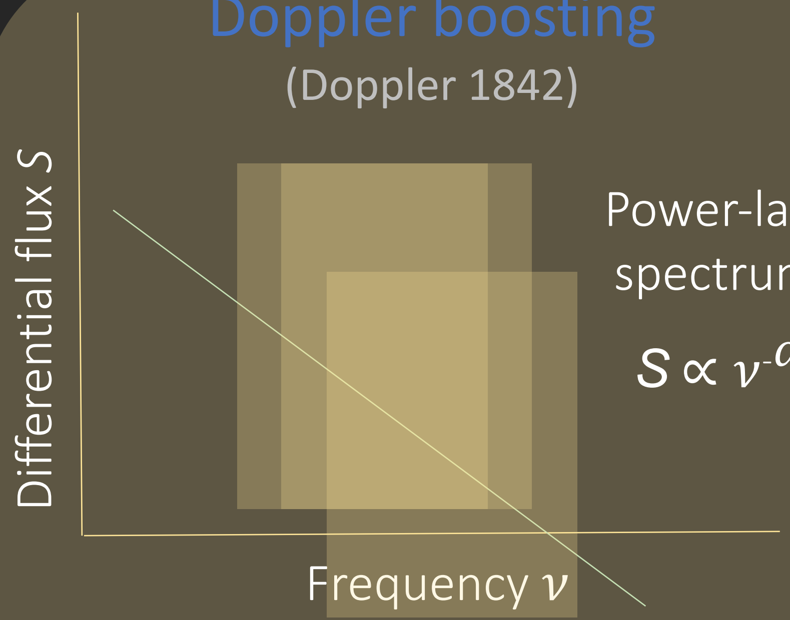


$$\tan\phi = \frac{\sin\theta}{\gamma(\cos\theta + \frac{v}{c})}$$

+

Doppler boosting

(Doppler 1842)

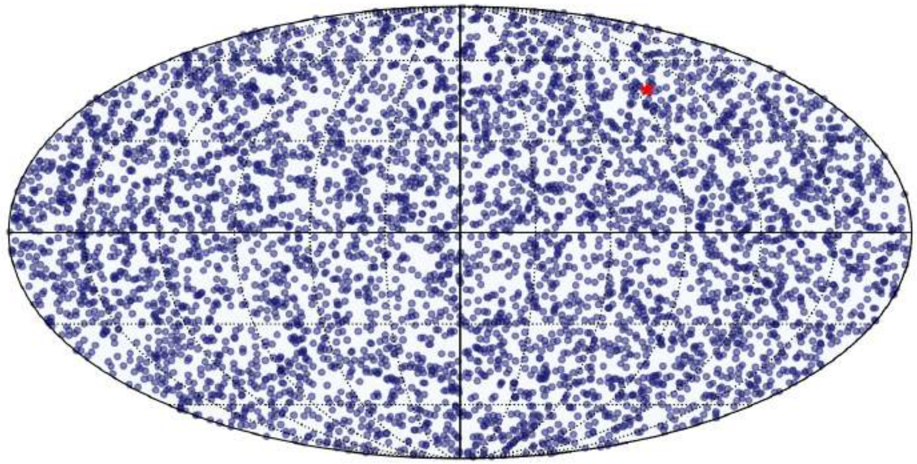


Integral flux distribution: $N(>S) \propto S^{-x}$

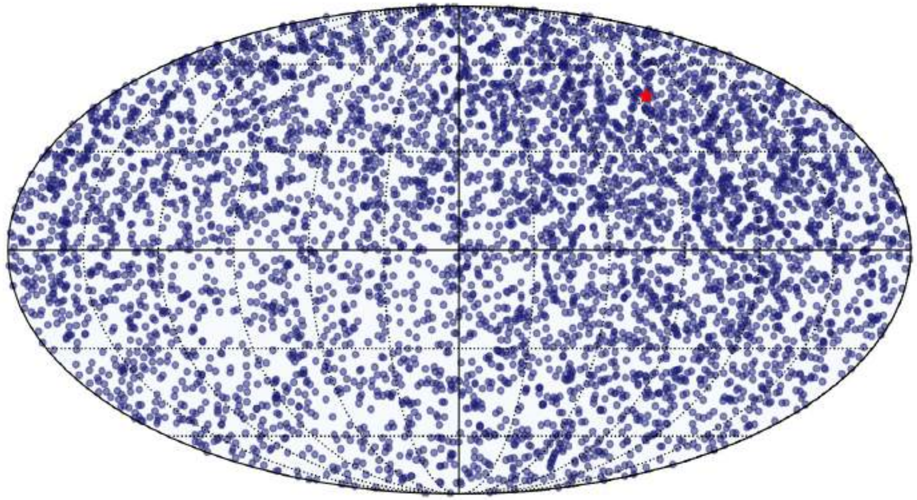
Flux-limited catalogue ➞ *more* sources in direction of motion

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

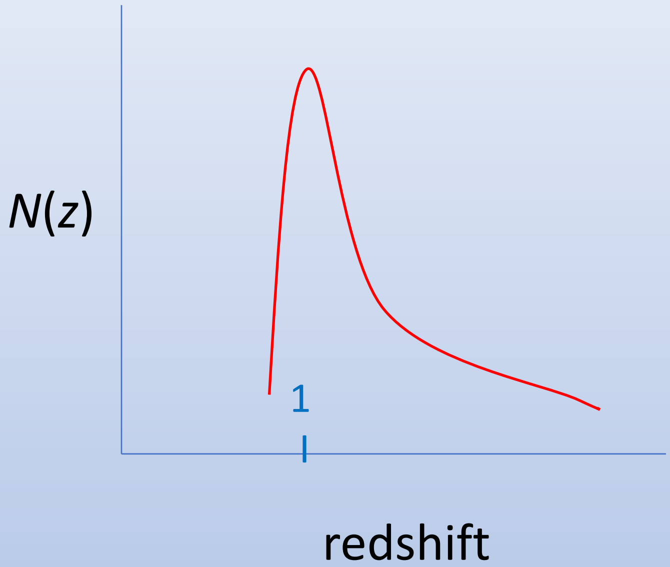
Galaxies / quasars in CMB “rest frame”



Aberration: object positions compressed in direction of motion
Doppler boosting: otherwise too-faint objects boosted into catalog flux limit



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



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

$\vec{\mathcal{K}} \rightarrow$ 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' $\propto 1/\sqrt{Ntot}$ 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.), $\vec{\mathcal{S}}(N(z)) \rightarrow 0$ (est.)

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

Wide Field Infrared Survey Explorer: 1,200,000 galaxies, <*z*> ~ 0.14, $\vec{\mathcal{S}}(N(z))$ significant

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

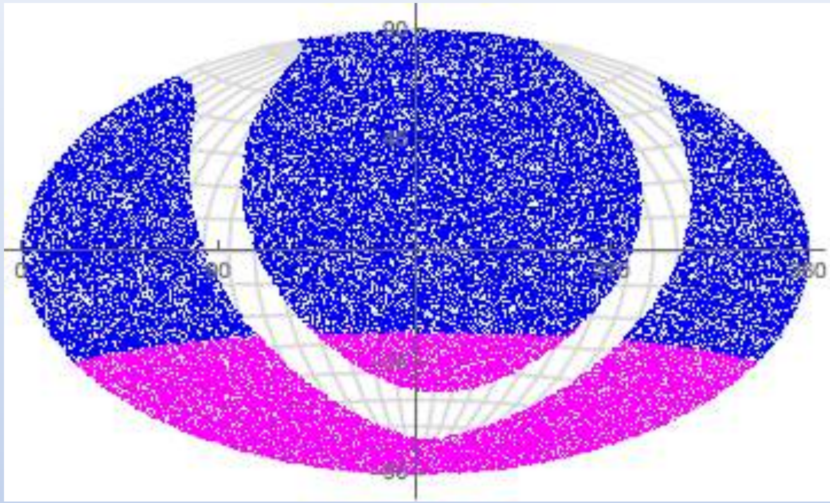
Wide Field Infrared Survey Explorer: 1,360,000 quasars, <*z*> ~ 1.2, $\vec{\mathcal{S}}(N(z))$ ~ 1%

Secrest, Rameez, von Hausegger, Mohayaee, S.S. & Colin, ApJ Lett.**908**:L51,2021

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

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

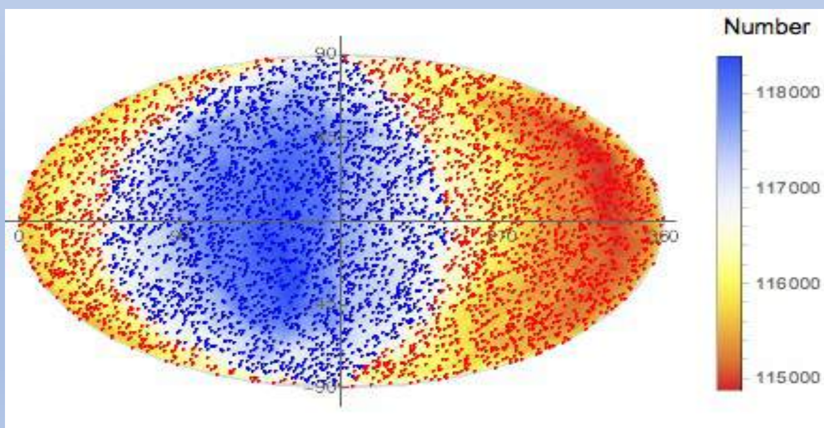
[Rescale the SUMSS fluxes by (843 MHz/1.4 GHz)$^{-0.75}$ = 1.46 to match with NVSS]

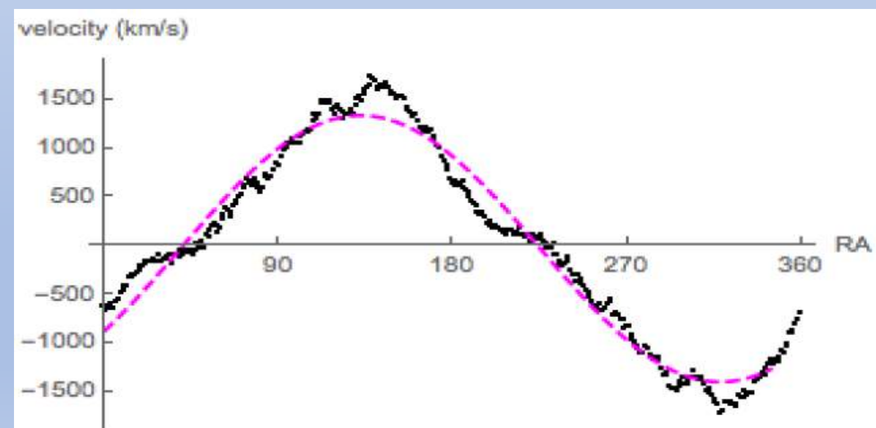


To get rid of any 'clustering dipole':

- 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



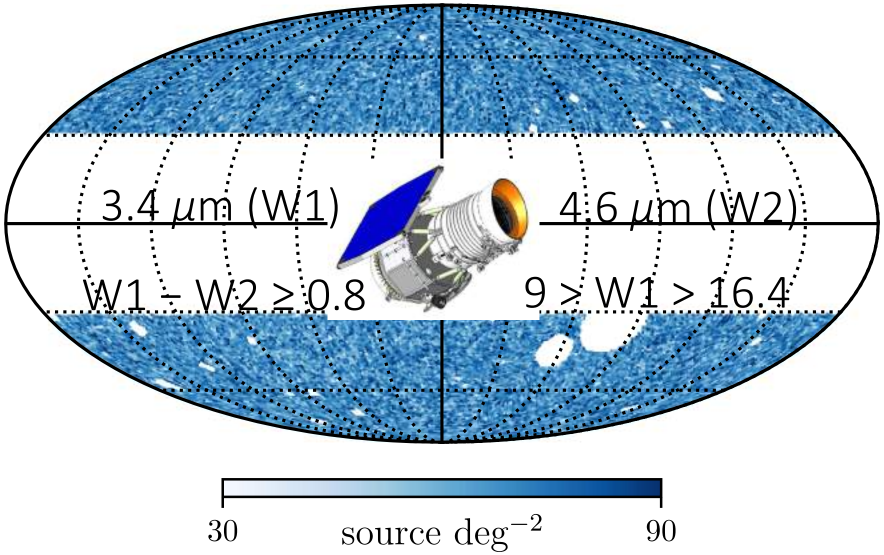


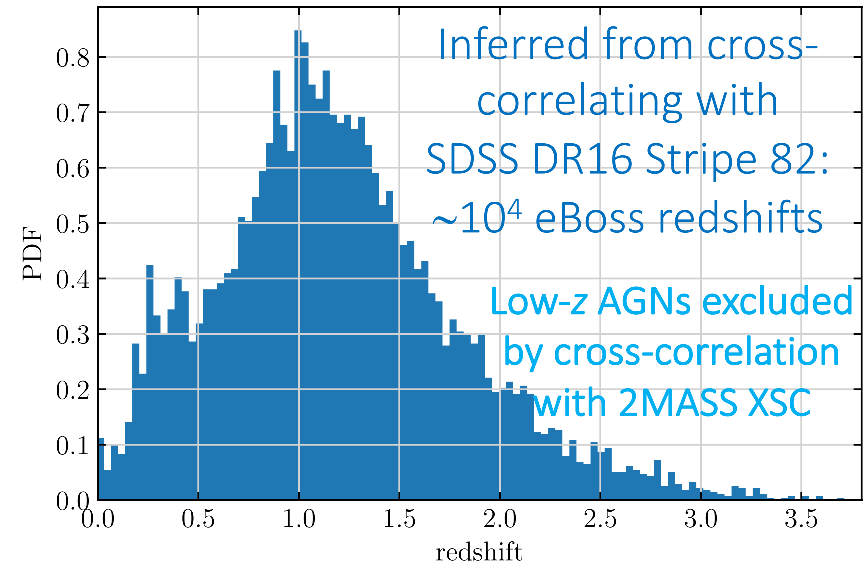
Confirms claim by Singal (ApJ **742**:L23,2011) … however source redshifts are not *directly* measured (also the statistical significance is only 2.8**σ** – by Monte Carlo)

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

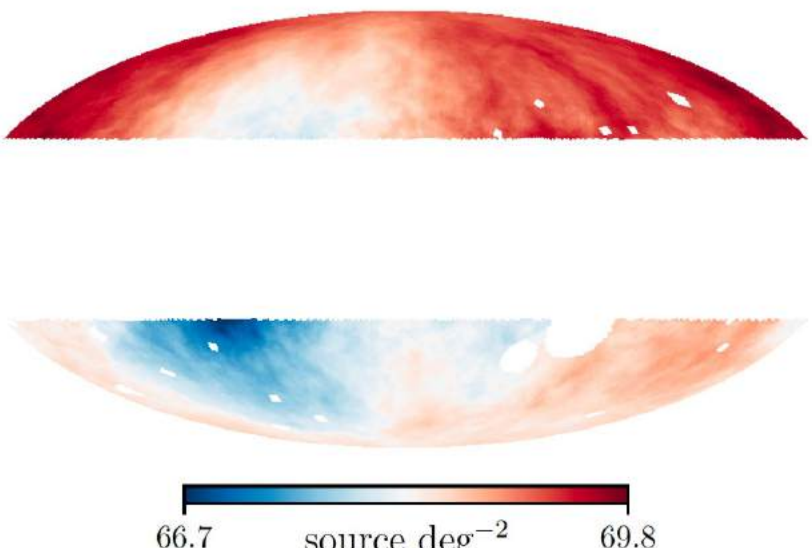
The CatWISE quasar catalogue

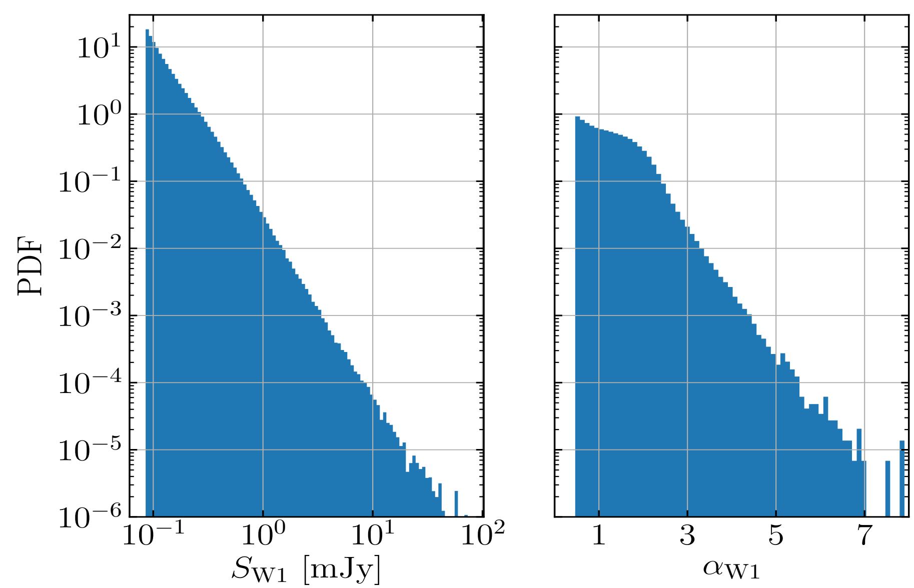
Secrest, Rameez, Von Hausegger, Mohayaee, S.S. & Colin, ApJL **908**:L51,2021





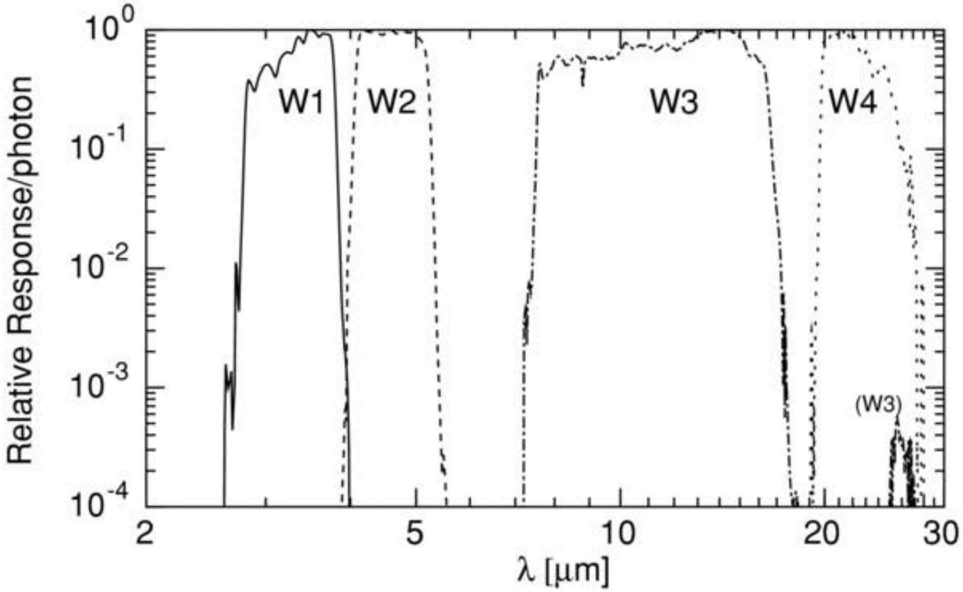
We now have a catalogue of ~1.5 million quasars, with 99% at redshift > 0.1

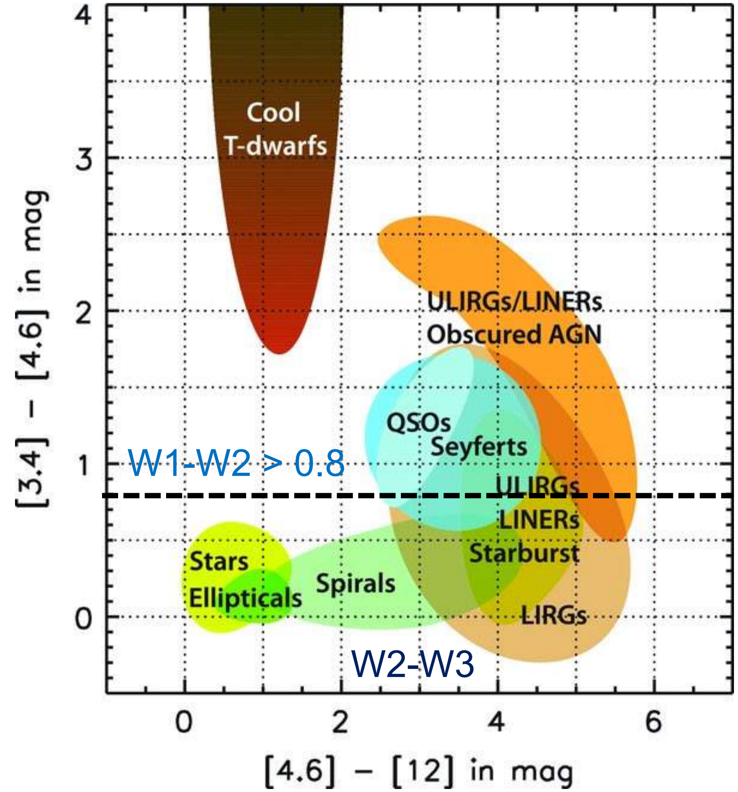




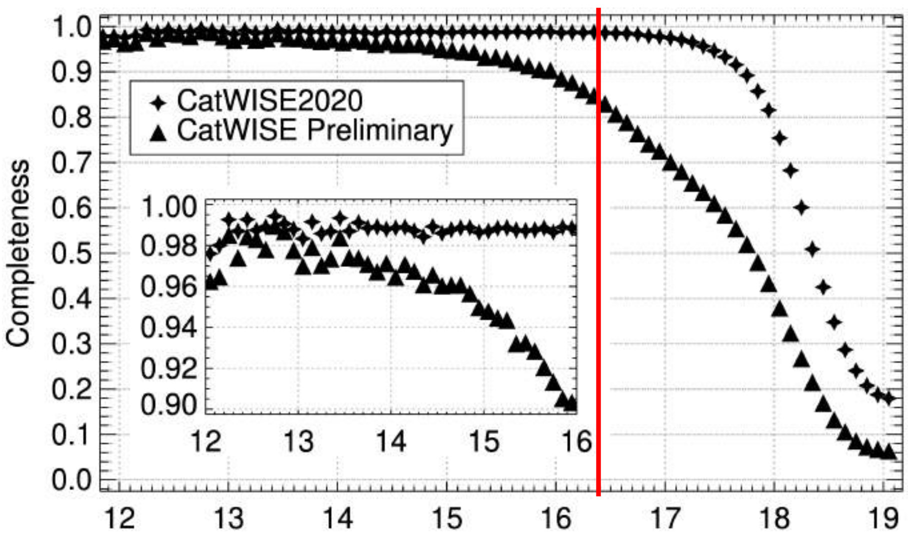
The dipole can be compared to that expected, knowing the spectrum & flux distribution

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

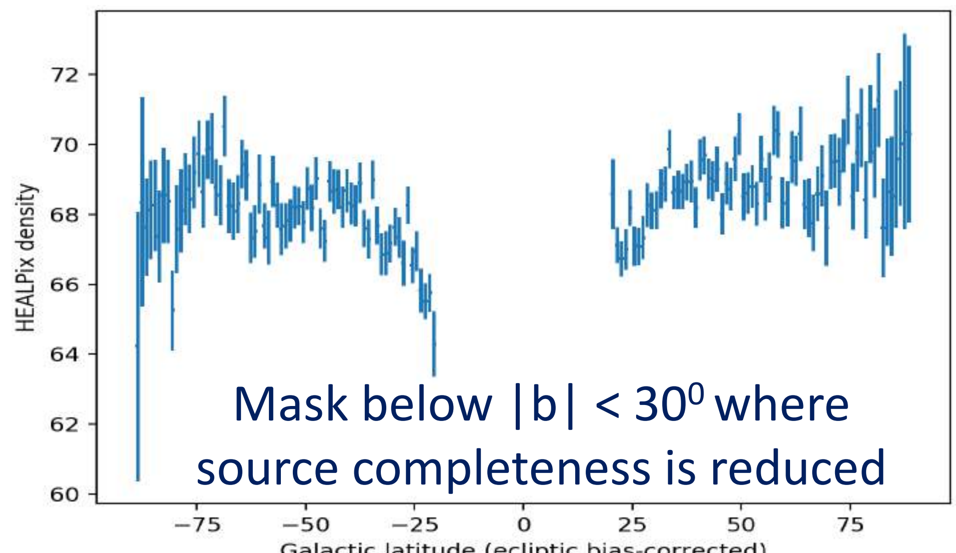




Wright *et al.*, AJ 140:1868,2010

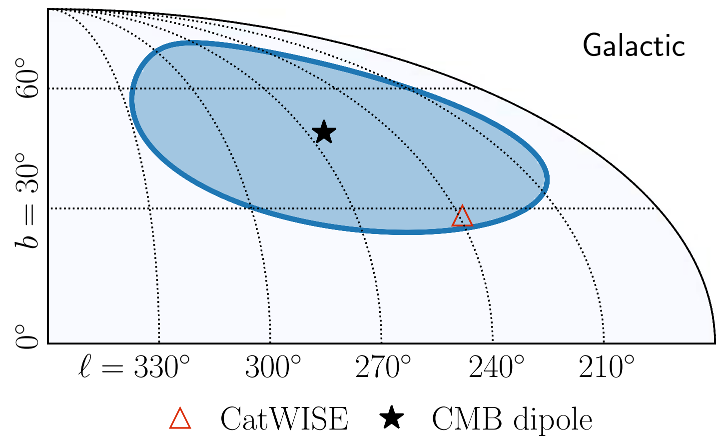


Magnitude cut W1 < 16.4 ensures completeness

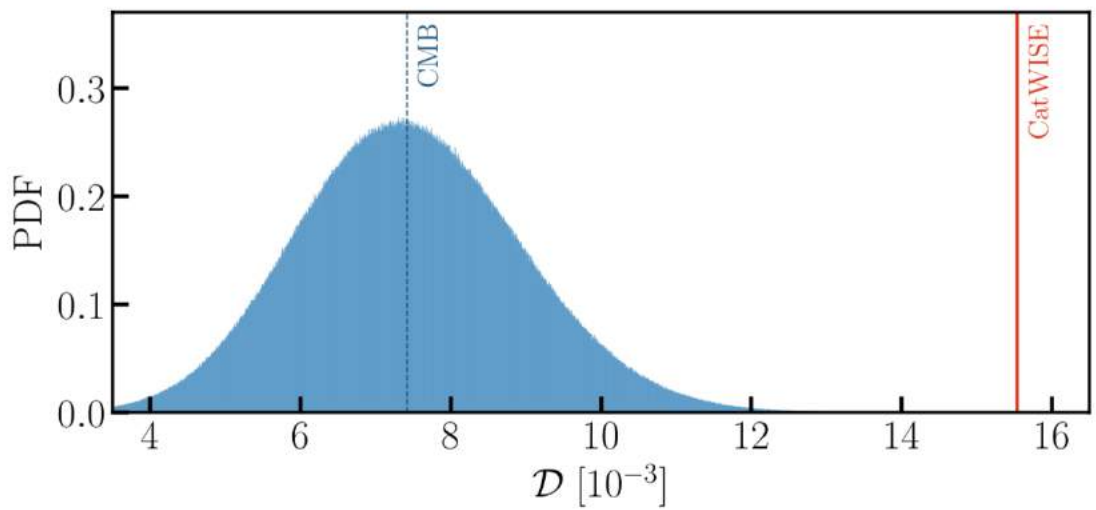


Mask below |b| < 30^0 where source completeness is reduced

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

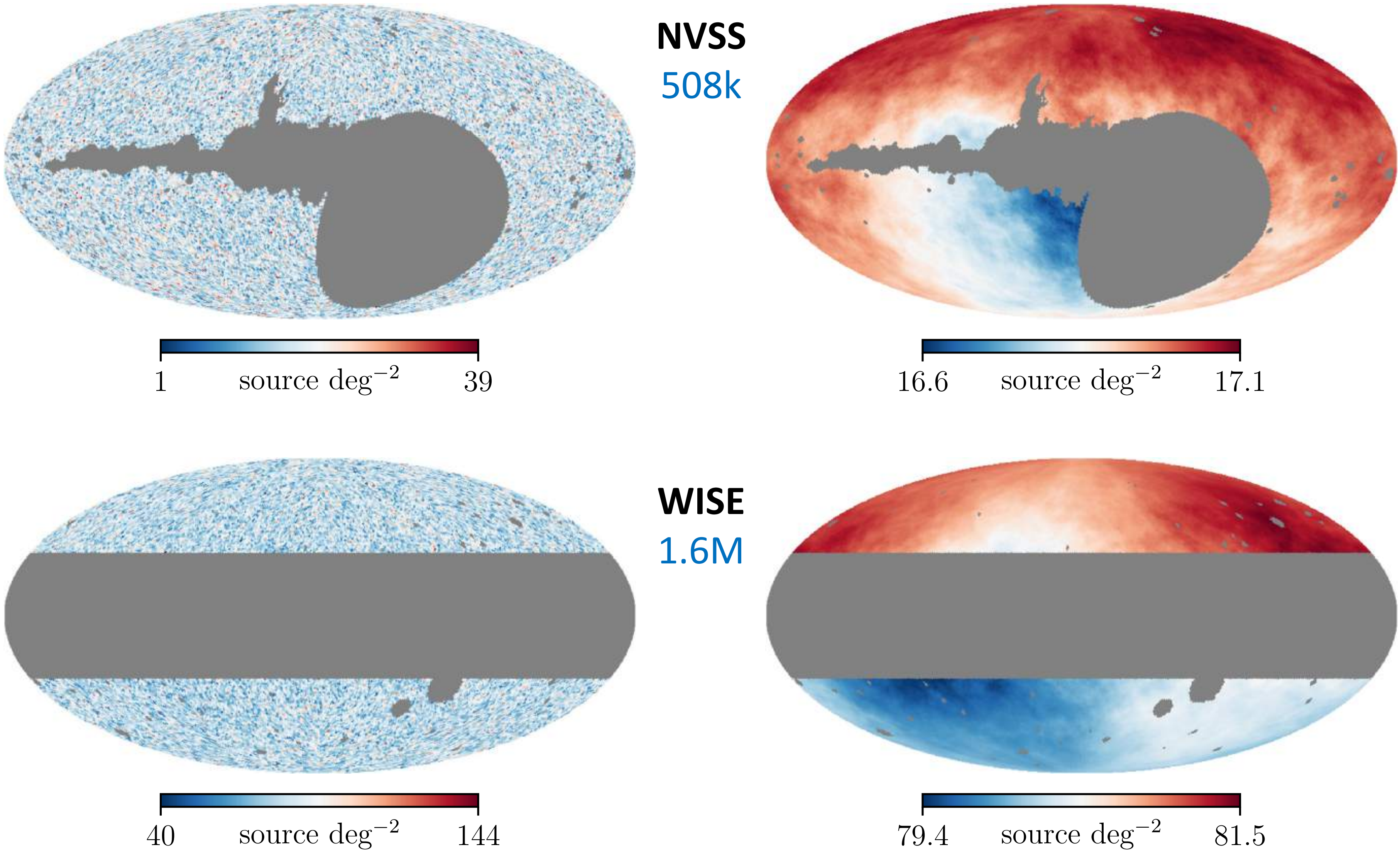


The kinematic interpretation of the CMB dipole is *rejected* with $p = 5 \times 10^{-7} \Rightarrow 4.9\sigma$

(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



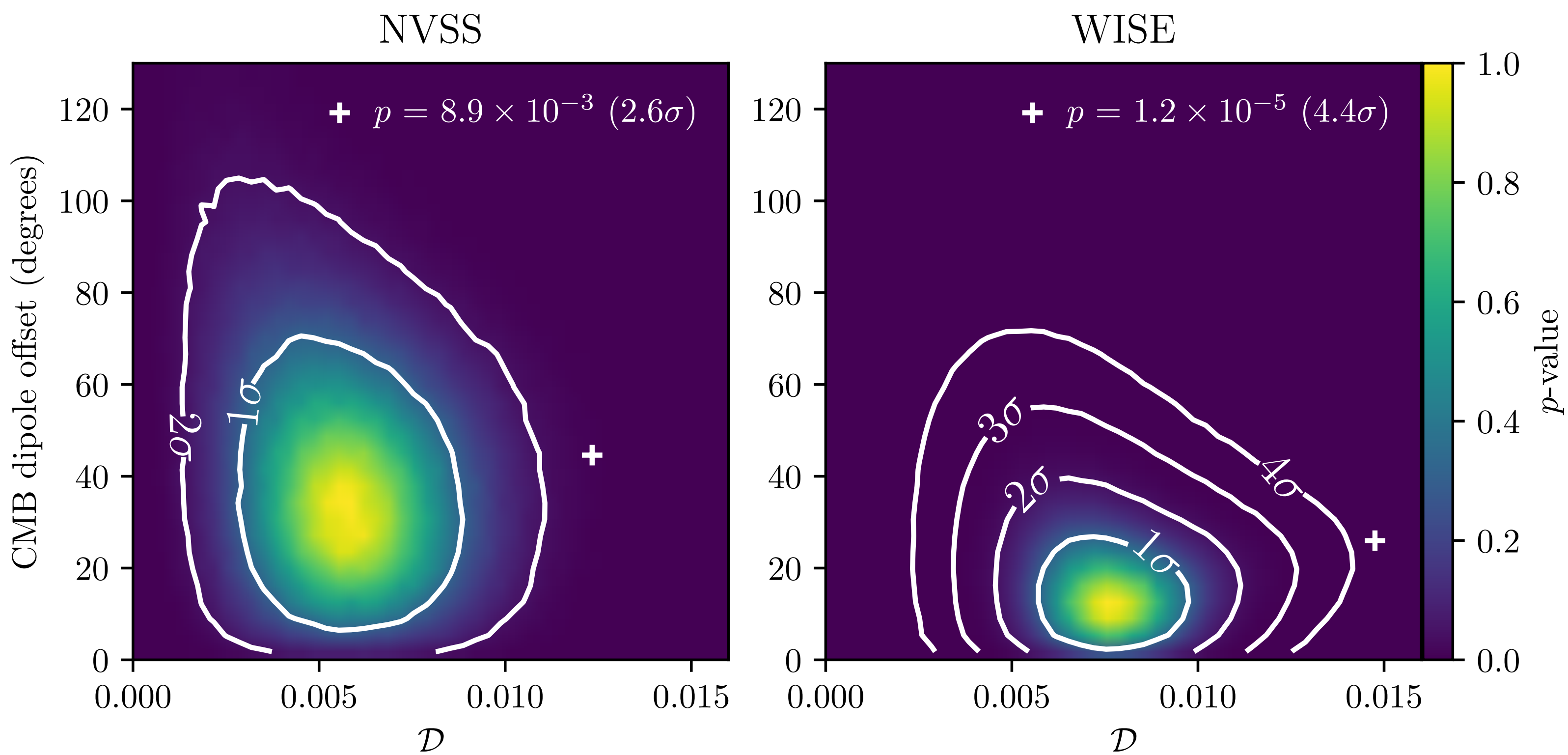
The two dipoles are *consistent* with each other; their vector mean is:

$D = (1.40 \pm 0.13)\times10^{-2}$ towards $(l, b) = (233.0,+34.4)$

The agreement *improves* if we subtract out the CMB dipole (assumed kinematic) from both

Secrest, Rameez, Von Hausegger, Mohayaee, S.S., Astrophys. J. Lett. 937 (2022) L31

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 **5.1σ**

Secrest, Rameez, Von Hausegger, Mohayaee, S.S., Astrophys. J. Lett. 937 (2022) L31

Anomalies in Physical Cosmology [arXiv:2208.05018]

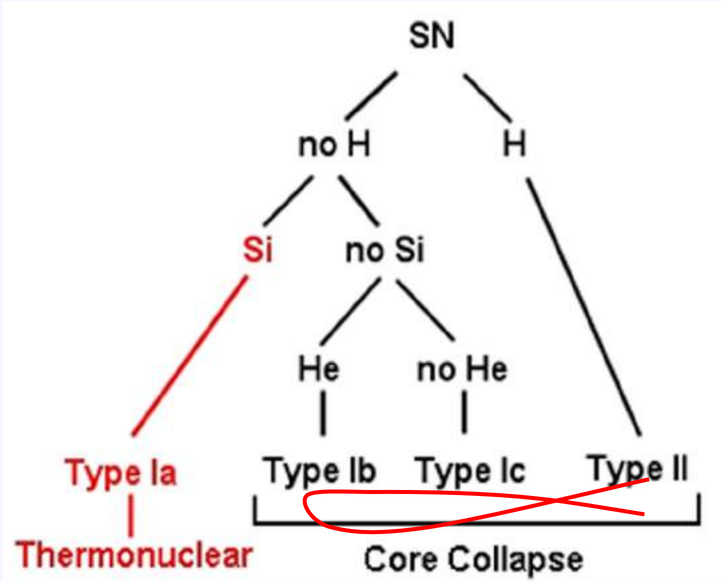
P. J. E. Peebles

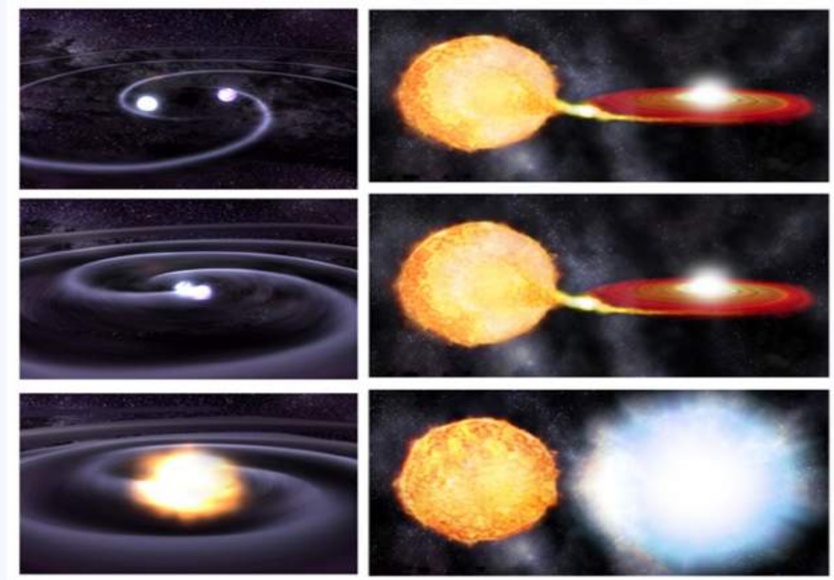
Joseph Henry Laboratories, Princeton University, Princeton, NJ 08544, USA

11 August 2022

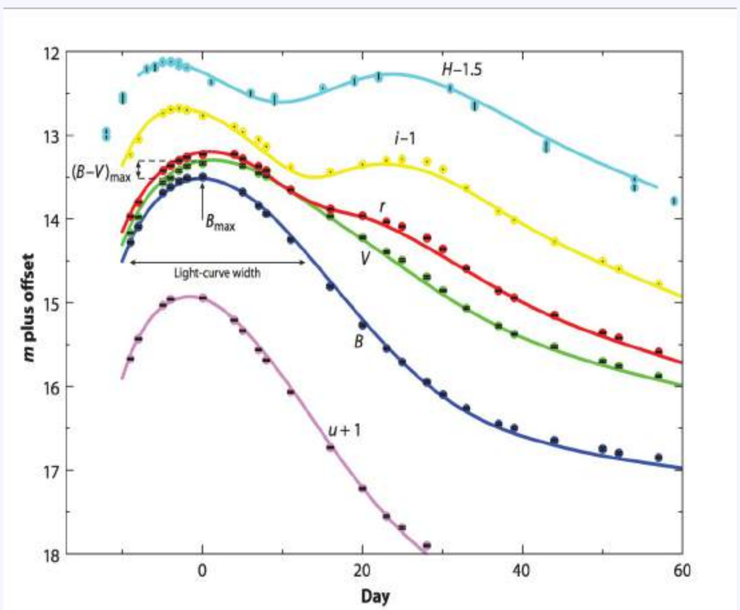
This anomaly is about as well established as the Hubble Tension, yet the literature on the kinematic effect is much smaller than the 344 papers with the phrase "Hubble Tension" in the abstract in the SAO/NASA Astrophysics Data System. (**I expect the difference is an inevitable consequence of the way we behave.**)

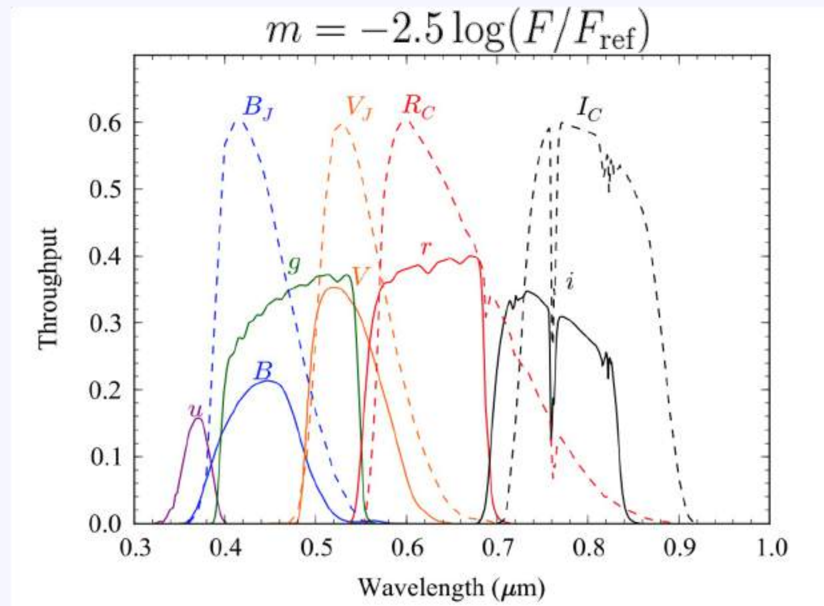
Cosmology with Type Ia supernovae





Goobar & Leibundgut, ARAA 61:251,2011

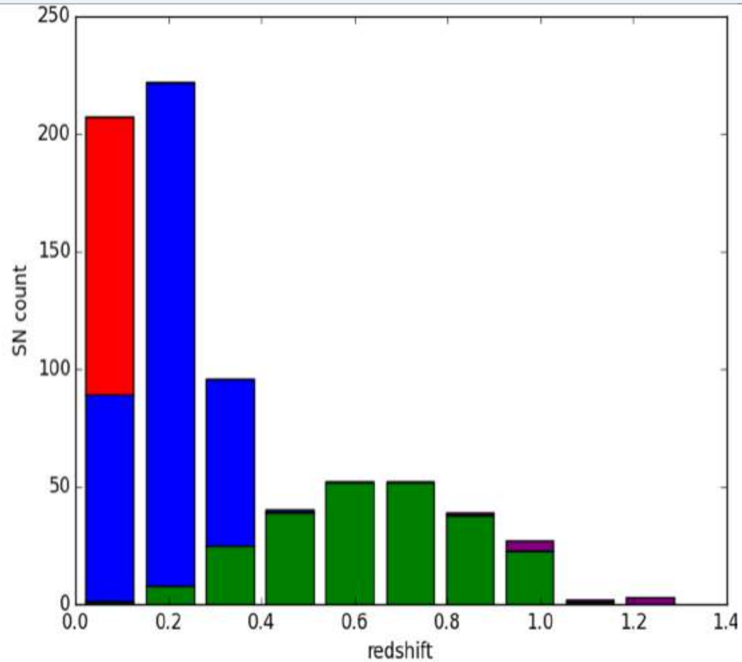


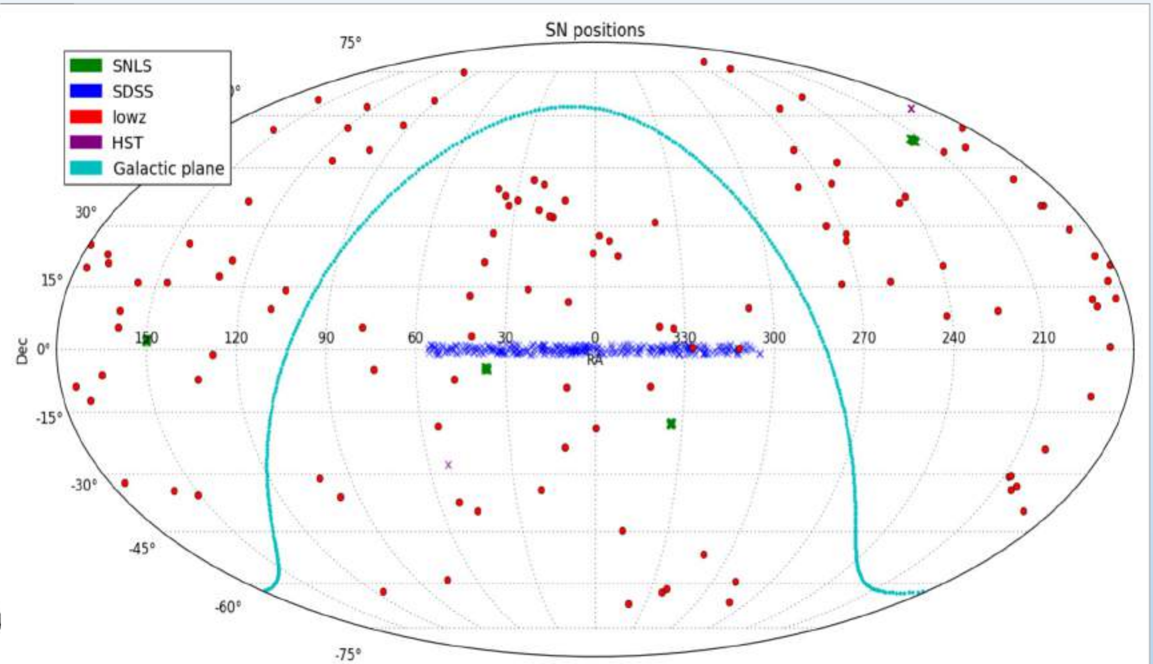


Identify by multiple exposure of sky (+ spectroscopy) ➙ measure peak **magnitude** and **redshift**

Supernova cosmology

Joint Lightcurve Analysis data (740 SNe Ia)





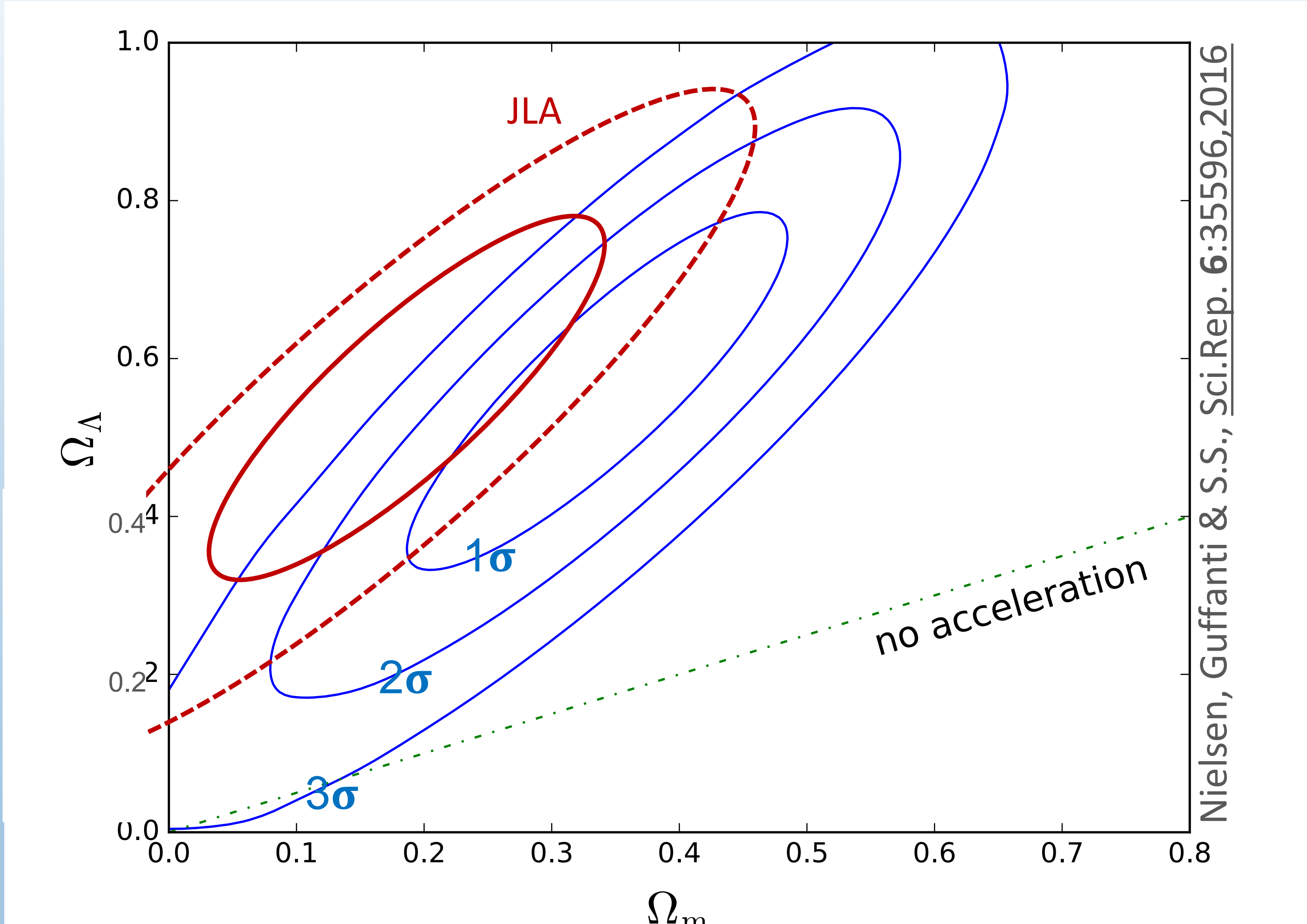
Betoule, Conley, Filippenko, Frieman, Goobar, Guy, Hook, Jha, Kessler, Pain, Perlmutter, Riess, Sollerman, Sullivan … A&A 568:A22,2014) http://supernovae.in2p3.fr/sdss_snls_jla/

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

NB: Supernova analyses use 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

We employ a Maximum Likelihood Estimator … and obtain rather different results

AVERAGED OVER THE SKY, THE DATA IS CONSISTENT WITH AN *UNIFORM* RATE OF EXPANSION



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

Profile Likelihood
MLE, *best fit*

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

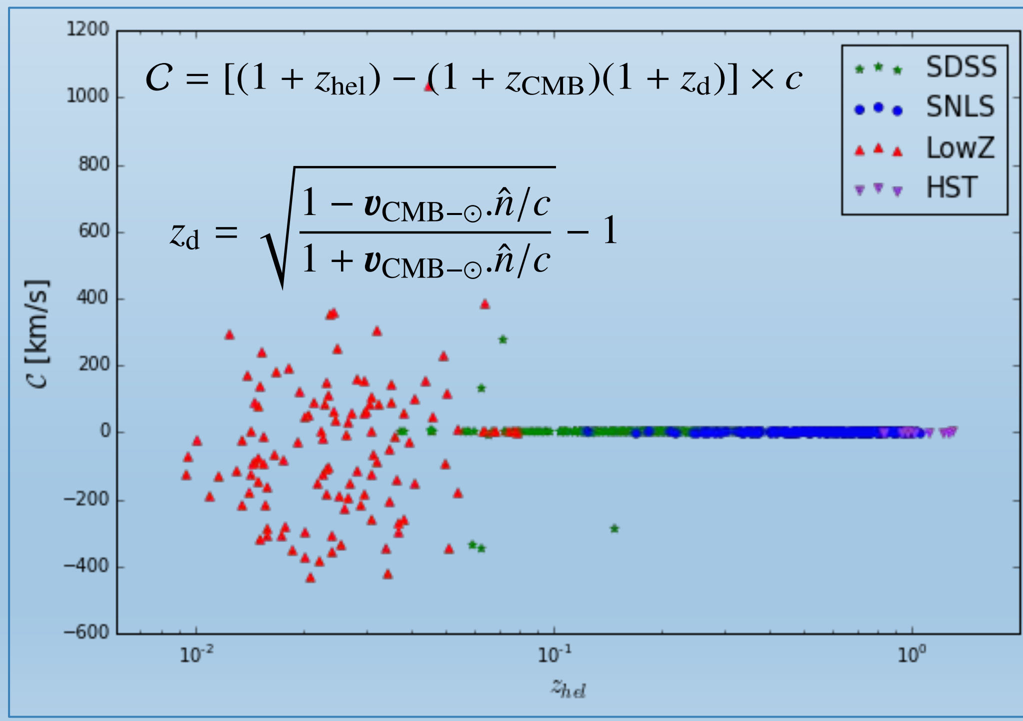
(Other constraints e.g. $\Omega_m \gtrsim 0.2$ or $\Omega_m + \Omega_\Lambda \simeq 1$ are relevant *only* to the ΛCDM model)

The measured redshift z_{hel} is converted to z_{CMB} ($\equiv z$) *assuming* the CMB dipole is due to our motion w.r.t. the **cosmic rest frame** in which the universe is supposedly isotropic:

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

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

Moreover the peculiar velocity 'corrections' applied to the JLA catalogue have assumed that we have converged to the CMB frame at 180/h Mpc (contrary to observations)



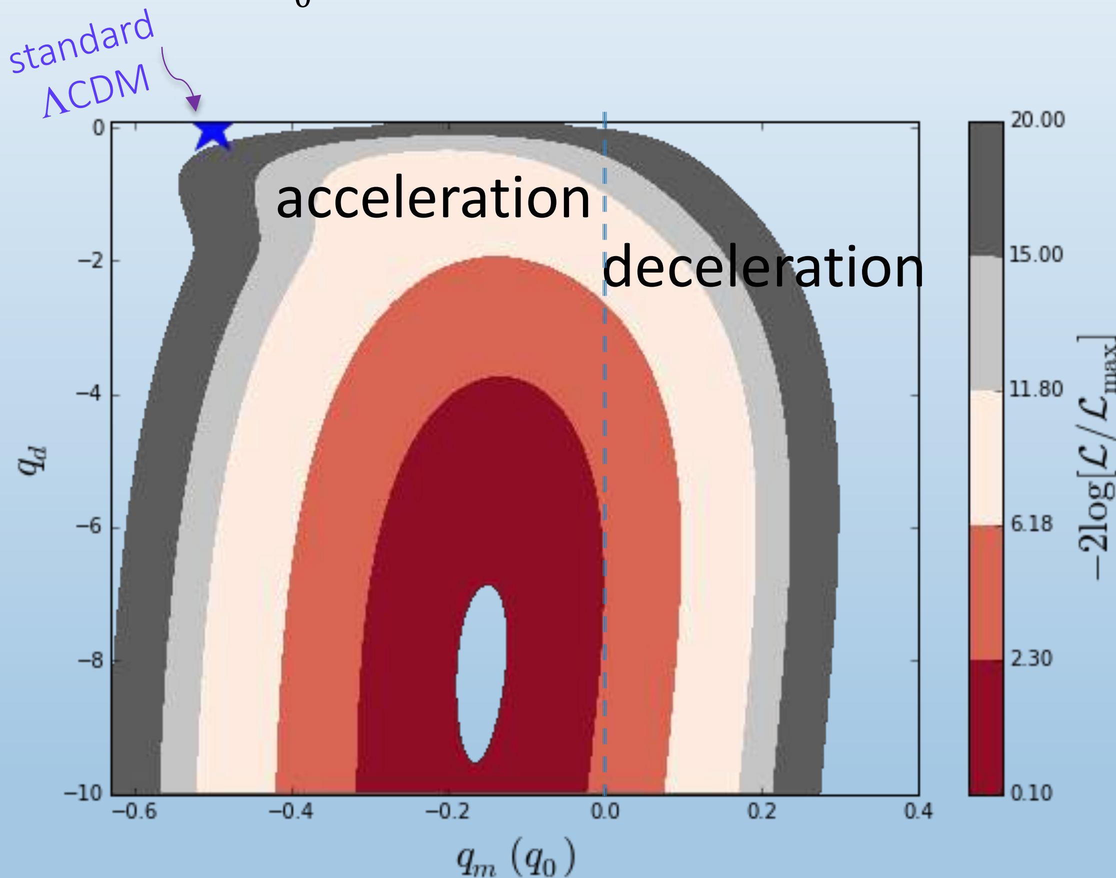
Colin *et al*, A&A **631**:L13,2019

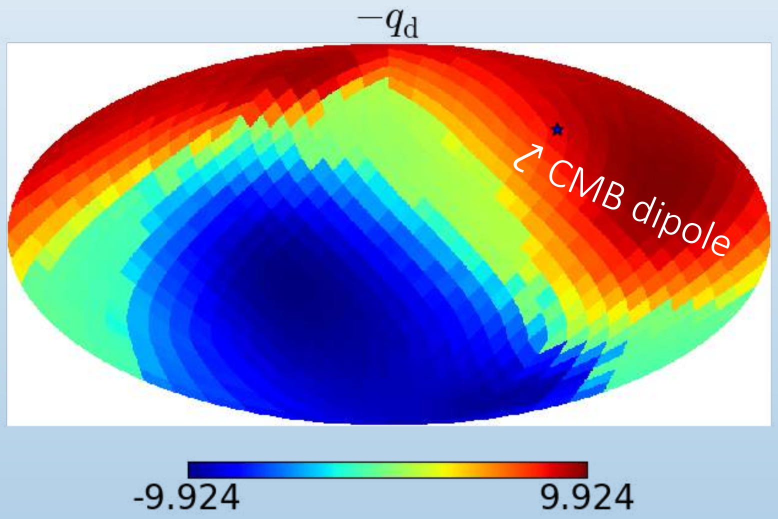
So we *undid* the corrections to recover the original data in the **heliocentric frame**

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

A cosmographic analysis of SNe Ia luminosity distances shows that the inferred acceleration is indeed aligned with the local bulk flow

$$d_L(z) = \frac{cz}{H_0}\left[1 + \frac{1}{2}(1 - q_0)z + \ldots\right], \; q_0 \equiv -(\ddot{a}a)/\dot{a}^2 \implies q_\mathrm{m} + \vec{q}_\mathrm{d}.\hat{n}\mathcal{F}(z, S)$$





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

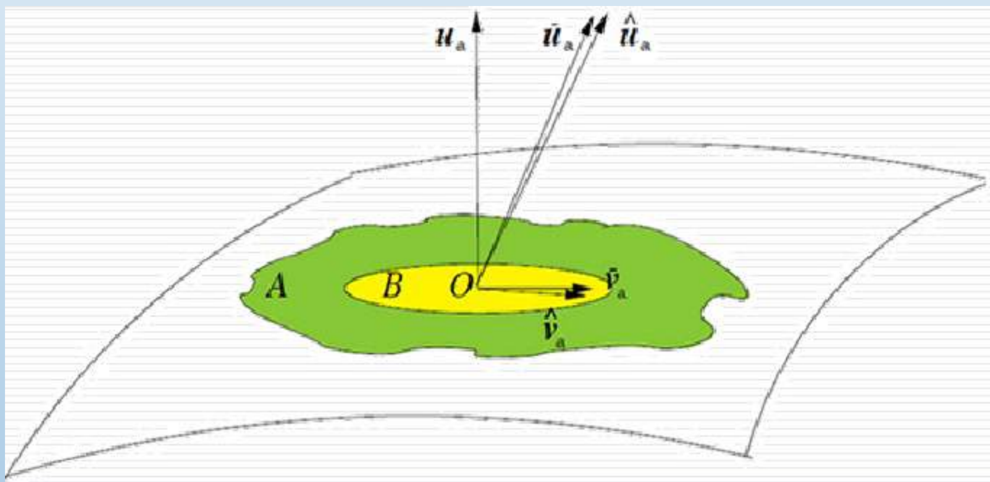
The significance of q_0 being negative has now *decreased* to only 1.4σ

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

Do we infer acceleration although the expansion is actually decelerating … because we are *'tilted observers'* in a bulk flow?

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

… 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

Summary

- The 'standard model' of cosmology was established before there was any data … and its assumptions (homogeneity, isotropy) have not been tested.

Now that we have data, it should be a priority to *test the cosmological model assumptions* – not simply measure the model parameters with `precision'

- The rest frame of distant quasars & radio sources ≠ CMB rest frame

… This is a challenge to the assumption of a FLRW metric

- The standard procedure of boosting measured redshifts and magnitudes of SNe Ia to the 'cosmic rest frame', and making corrections for the peculiar velocities of their host galaxies to infer cosmic acceleration (which is then interpreted as due to Λ), is *unjustified*

The measurements made in the heliocentric rest frame reveal a dipole asymmetry in the recession velocities and in the inferred acceleration

$\Rightarrow$ cosmic acceleration may be just an artefact of our local bulk flow

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

… following Ellis & Stoeger: 'The fitting problem' (CQG 4:1697,1987)

Wir müssen wissen. Wir werden Wissen

We must know. We will know.

David Hilbert (Radio address in Königsberg, 1930)