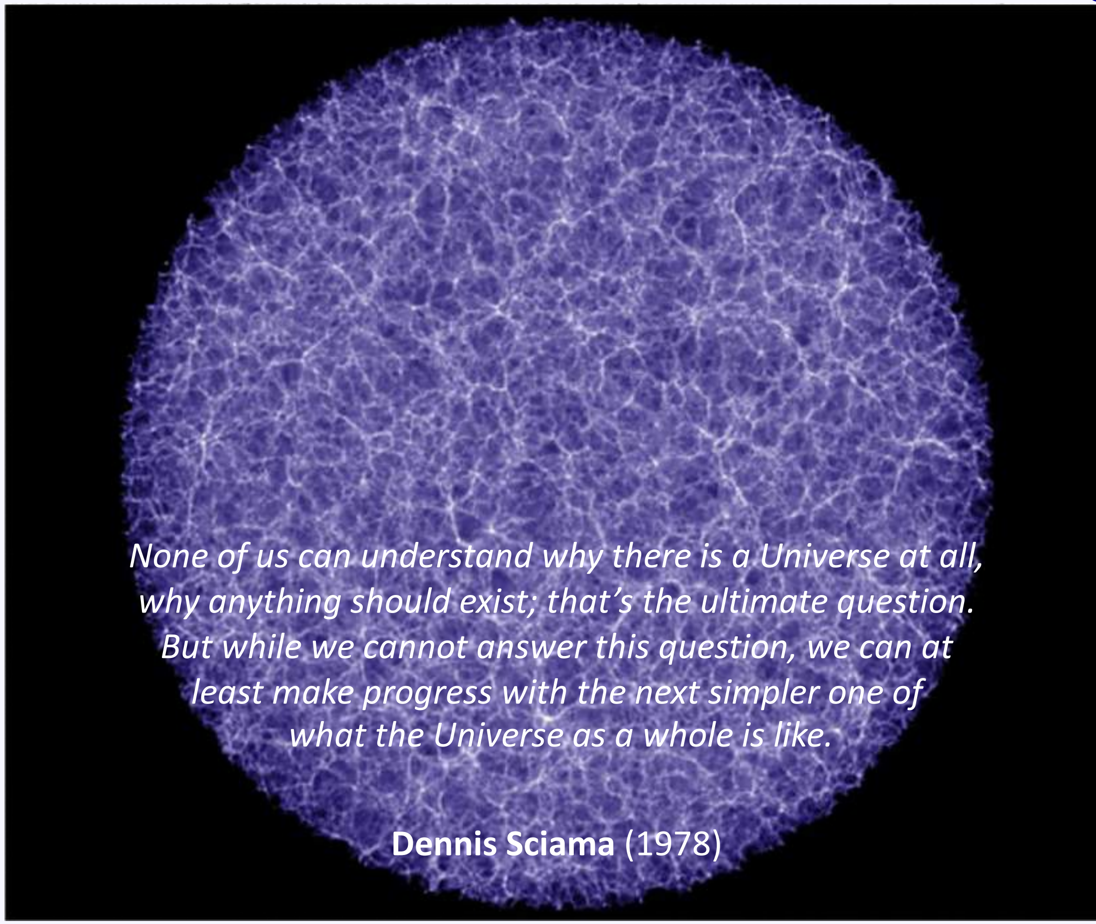
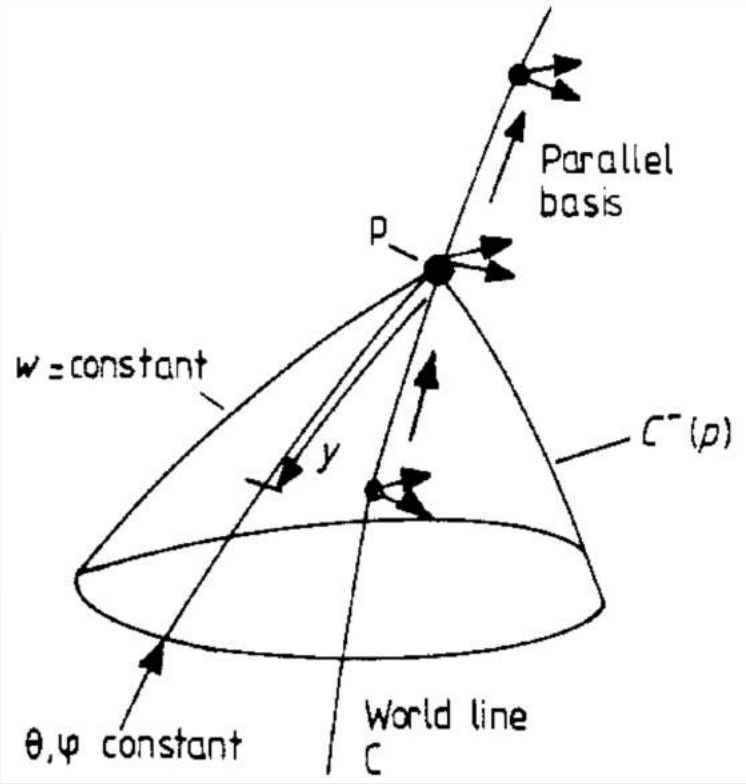
Beyond the cosmological standard model



Subir Sarkar

Rudolf Peierls Centre for Theoretical Physics, University of Oxford

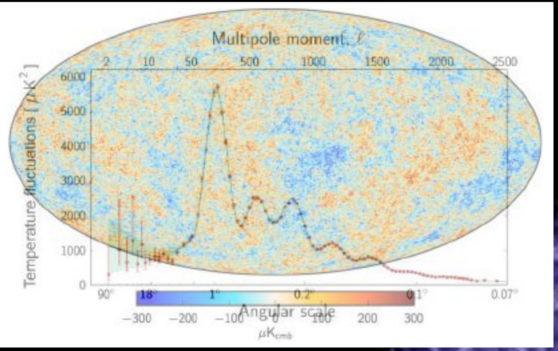
ALL WE CAN *EVER* LEARN ABOUT THE UNIVERSE IS CONTAINED WITHIN OUR PAST LIGHT CONE



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)



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

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

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

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

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

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

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

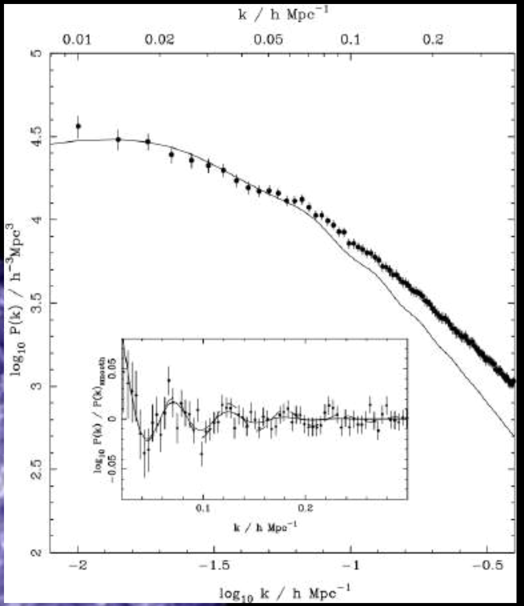
$$\ddot{a} = -\frac{4\pi G}{3}(\rho + 3P)\, a$$

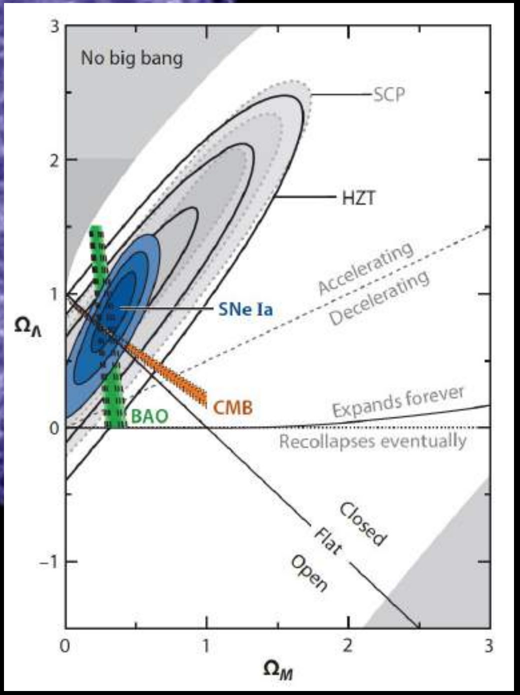
$$\mathbf{\Omega_m + \Omega_k + \Omega_\Lambda = 1}$$

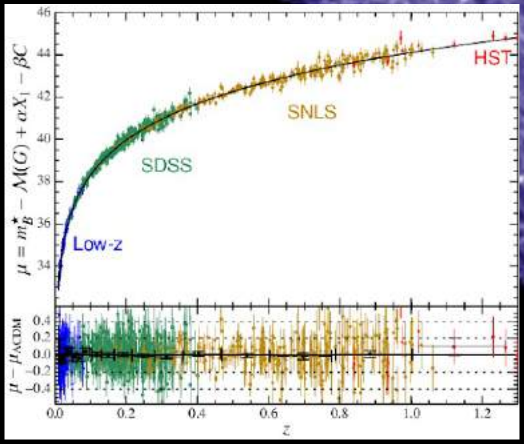
$0.8\Omega_{\mathrm{m}} - 0.6\Omega_\Lambda \approx -0.2$ (SNe Ia),
$\Omega_{\mathrm{k}} \approx 0.0$ (CMB), $\Omega_{\mathrm{m}} \sim 0.3$ (Clusters, BAO)

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

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

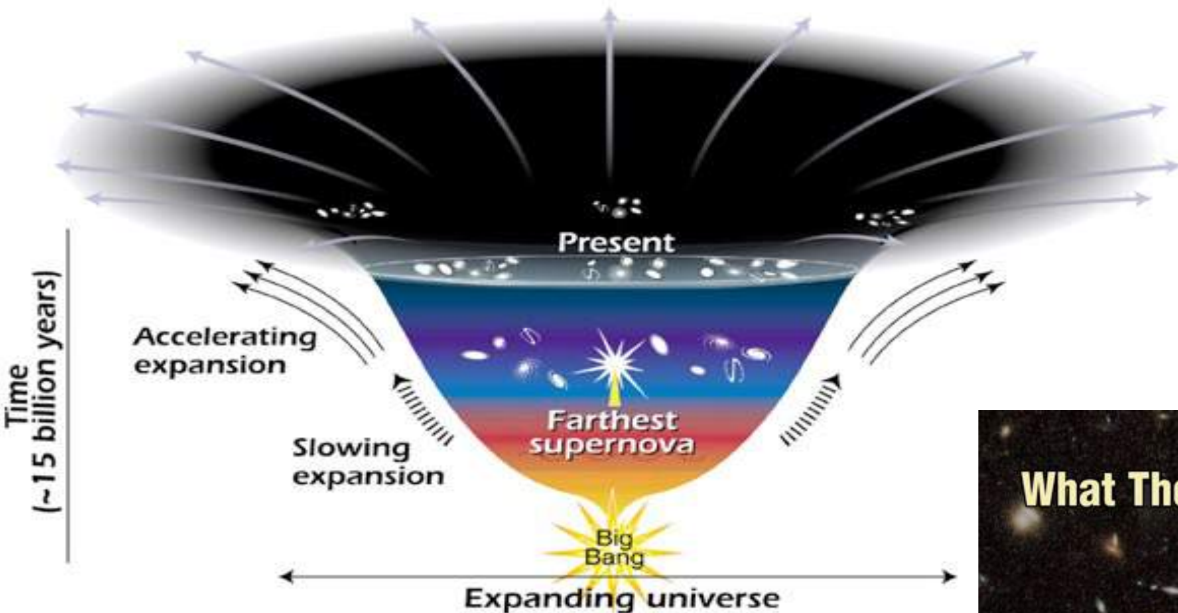






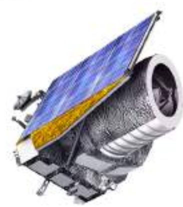
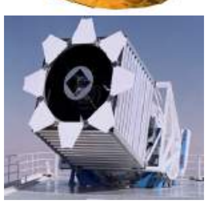
It is the Cosmic Sum sum rule that is used to *infer* a non-zero Λ of order H_0^2 from observations of SNe Ia, CMB, BAO, lensing etc …

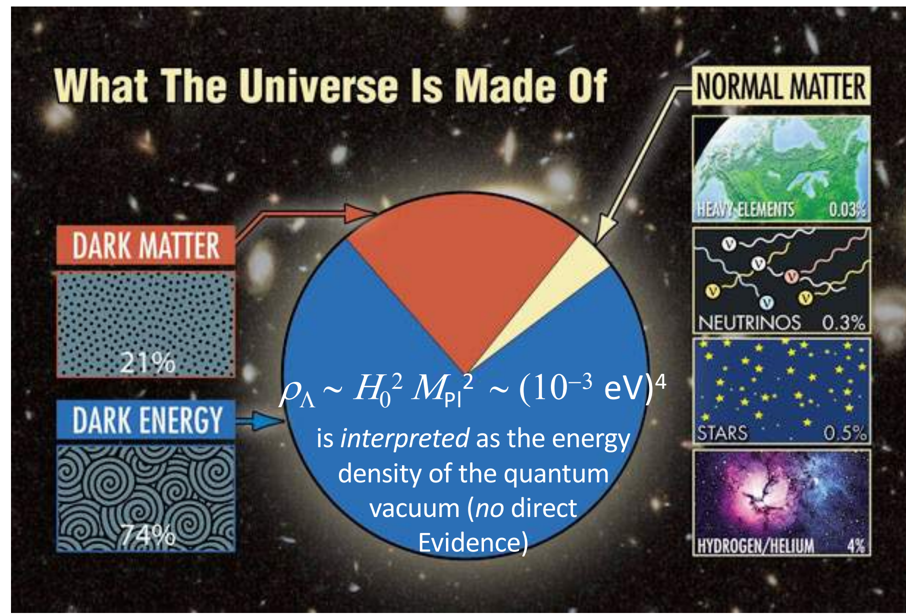
There is as yet no compelling *dynamical* evidence for Λ (e.g. the late-ISW effect)



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`

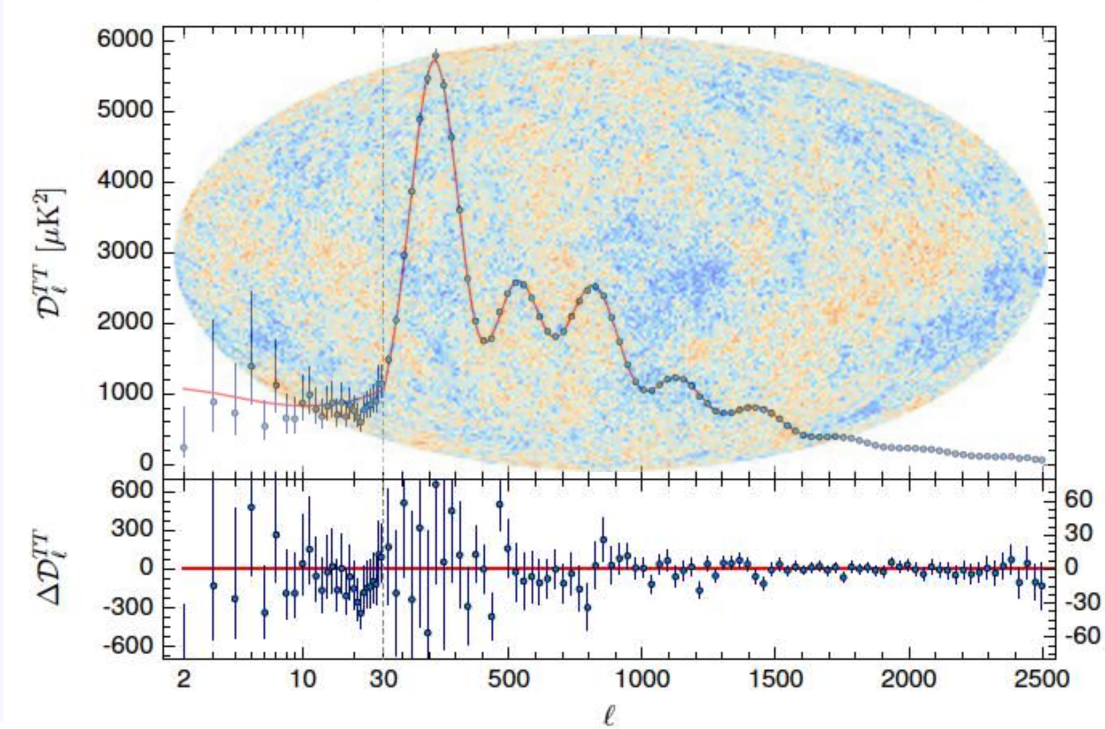




There has been substantial investment in major satellites and telescopes to *measure the parameters* of this standard cosmological model with increasing precision … but surprisingly little work on ***testing its foundational assumptions***

All data is well-fit by the 10-param. ΛCDM model + power-law $P(k)$



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

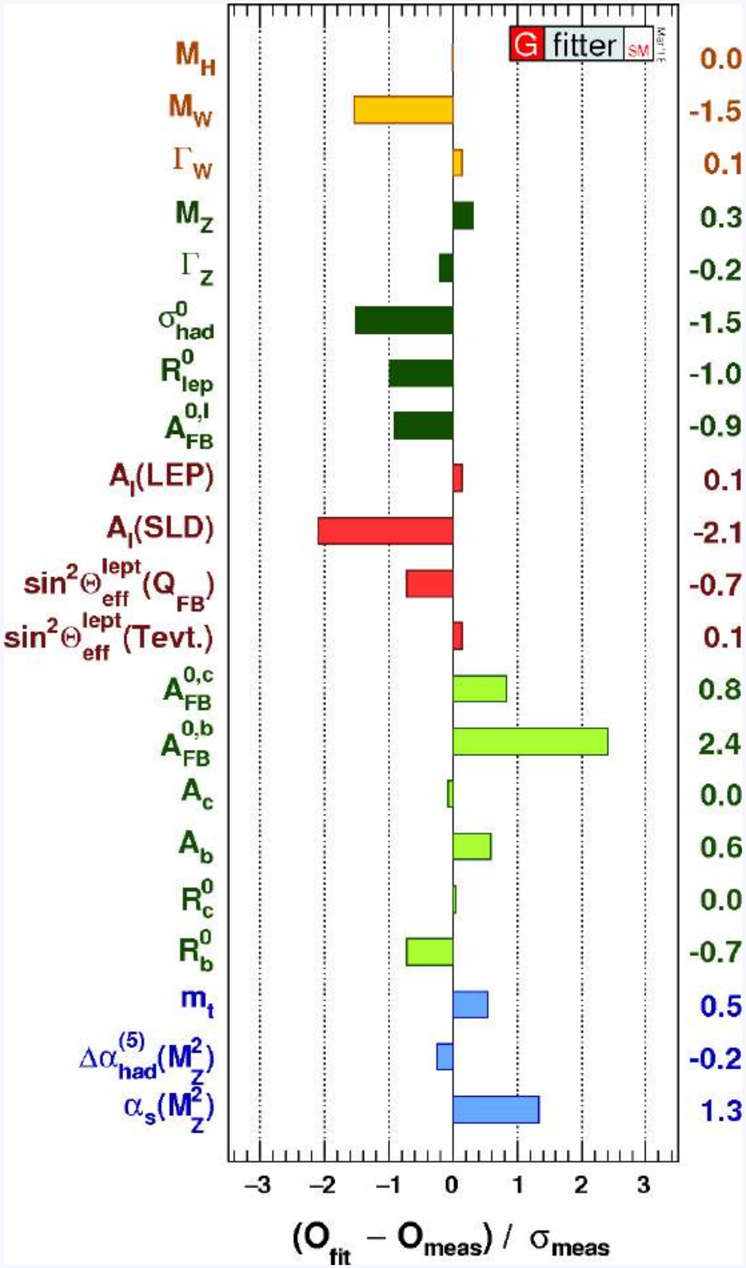
Parameter	[1] *Planck* TT+lowP	[2] *Planck* TE+lowP	[3] *Planck* EE+lowP	[4] *Planck* TT,TE,EE+lowP
$\Omega_b h^2$	0.02222 ± 0.00023	0.02228 ± 0.00025	0.0240 ± 0.0013	0.02225 ± 0.00016
$\Omega_c h^2$	0.1197 ± 0.0022	0.1187 ± 0.0021	$0.1150^{+0.0048}_{-0.0055}$	0.1198 ± 0.0015
$100\theta_{MC}$	1.04085 ± 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

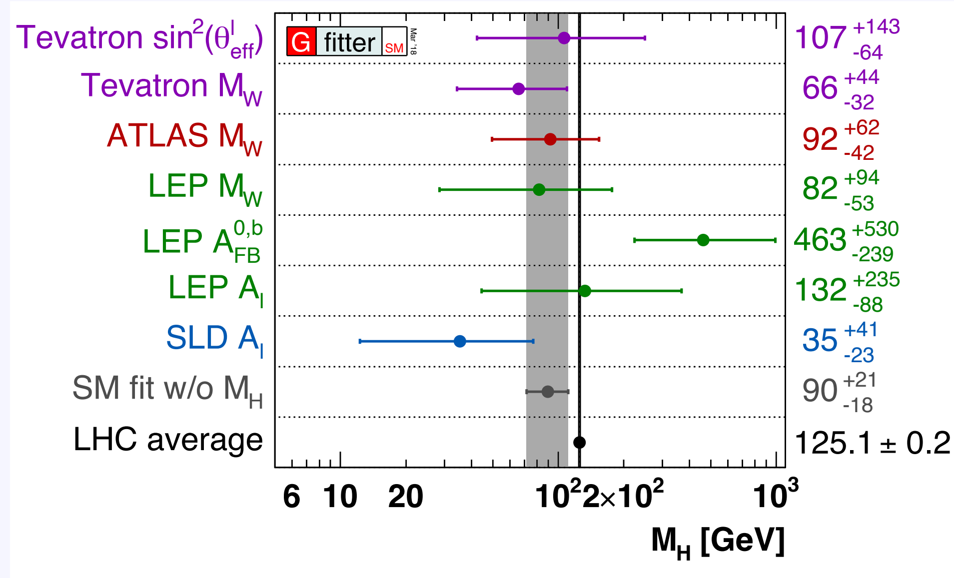
Note there is no entry for Λ

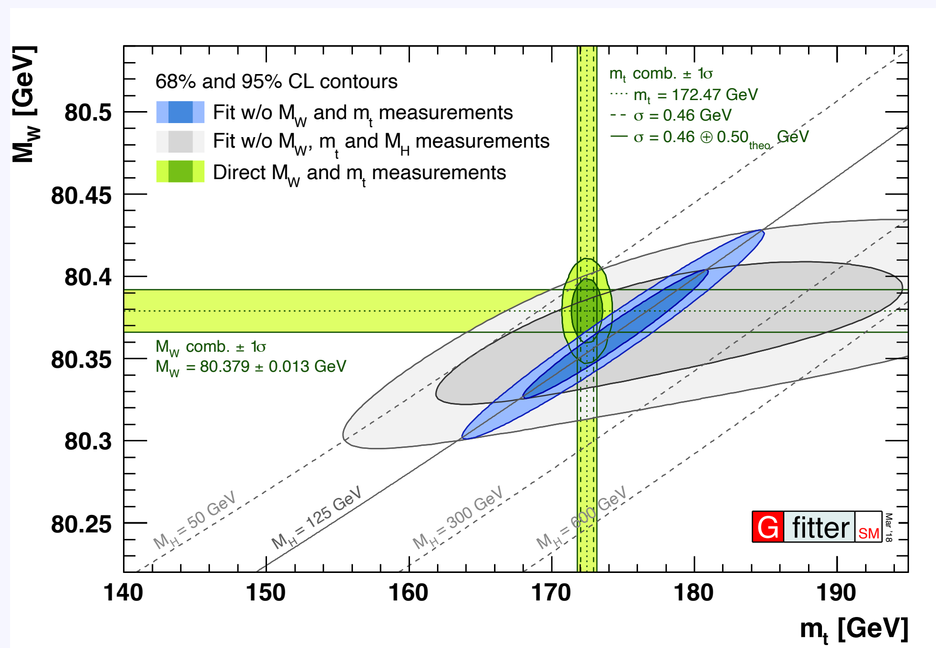
There is no *direct* sensitivity of CMB anisotropy to dark energy … it is all *inferred* (using $\Omega_m + \Omega_k + \Omega_\Lambda \equiv 1$)

(To detect the late-ISW correlations between CMB & structure induced by **Λ** will require 10 million redshifts)

Results for the Global Electroweak Standard Model Fit

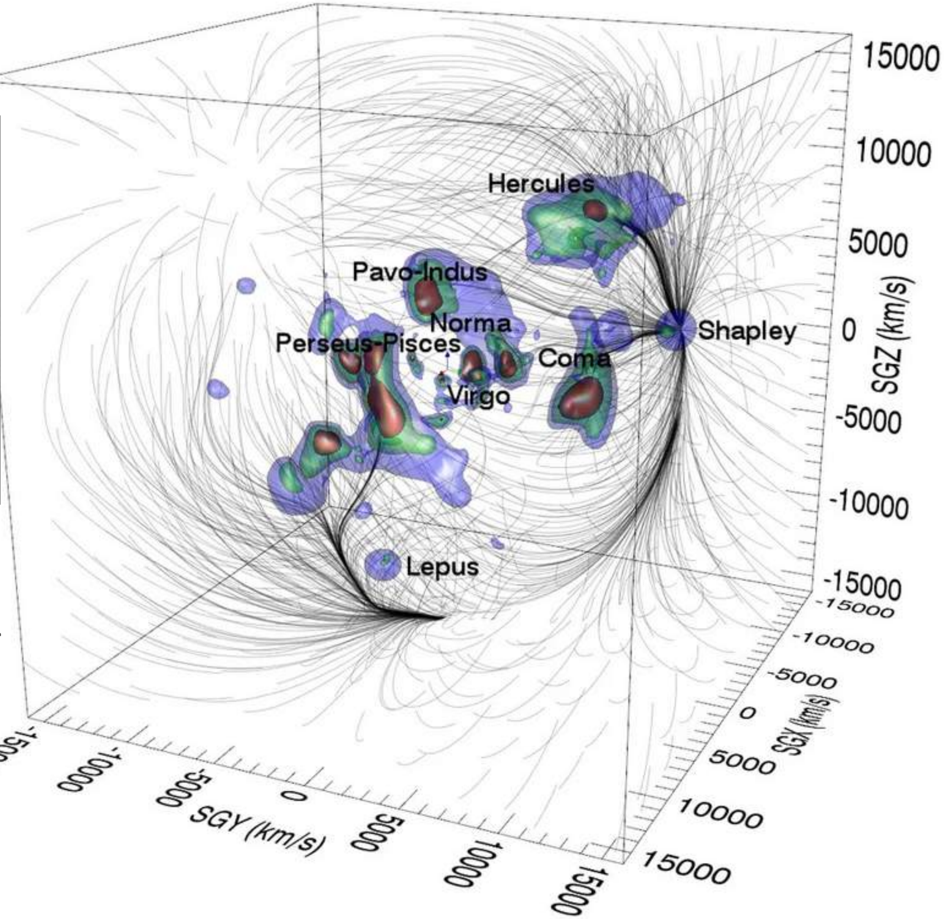






Do we reject *any* possibility of deviations from the SM … because it all fits so well?!

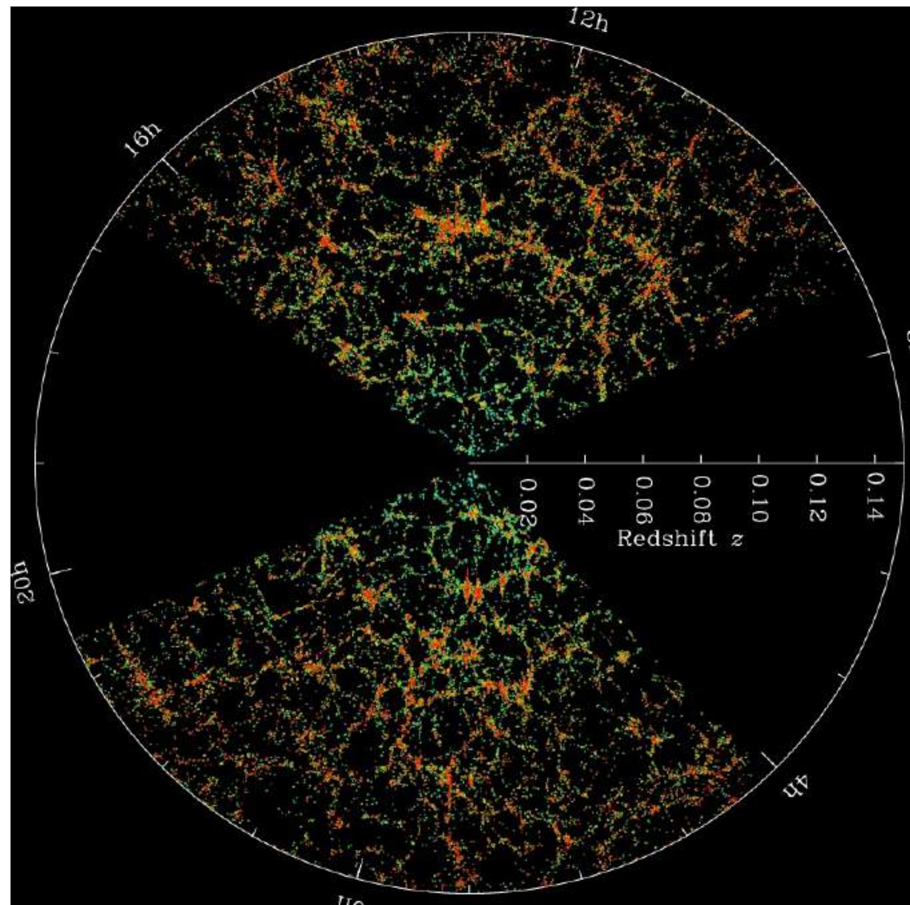
How well does the real universe conform to the standard FLRW model description?



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?

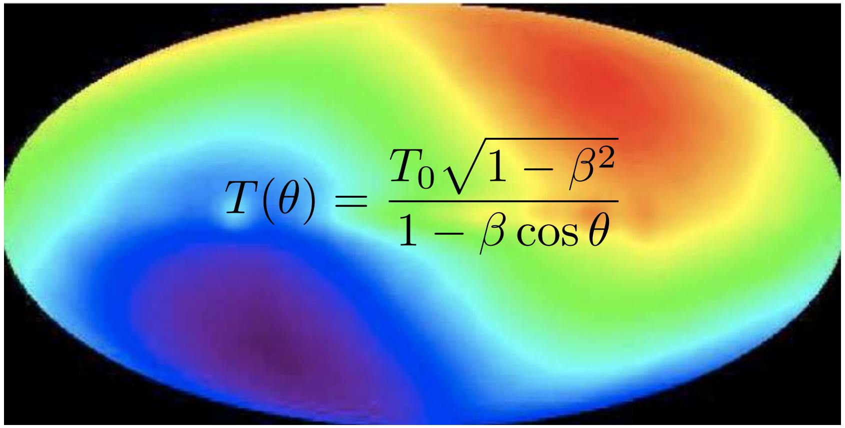
… To assume that we are a '*typical*' observer?

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

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

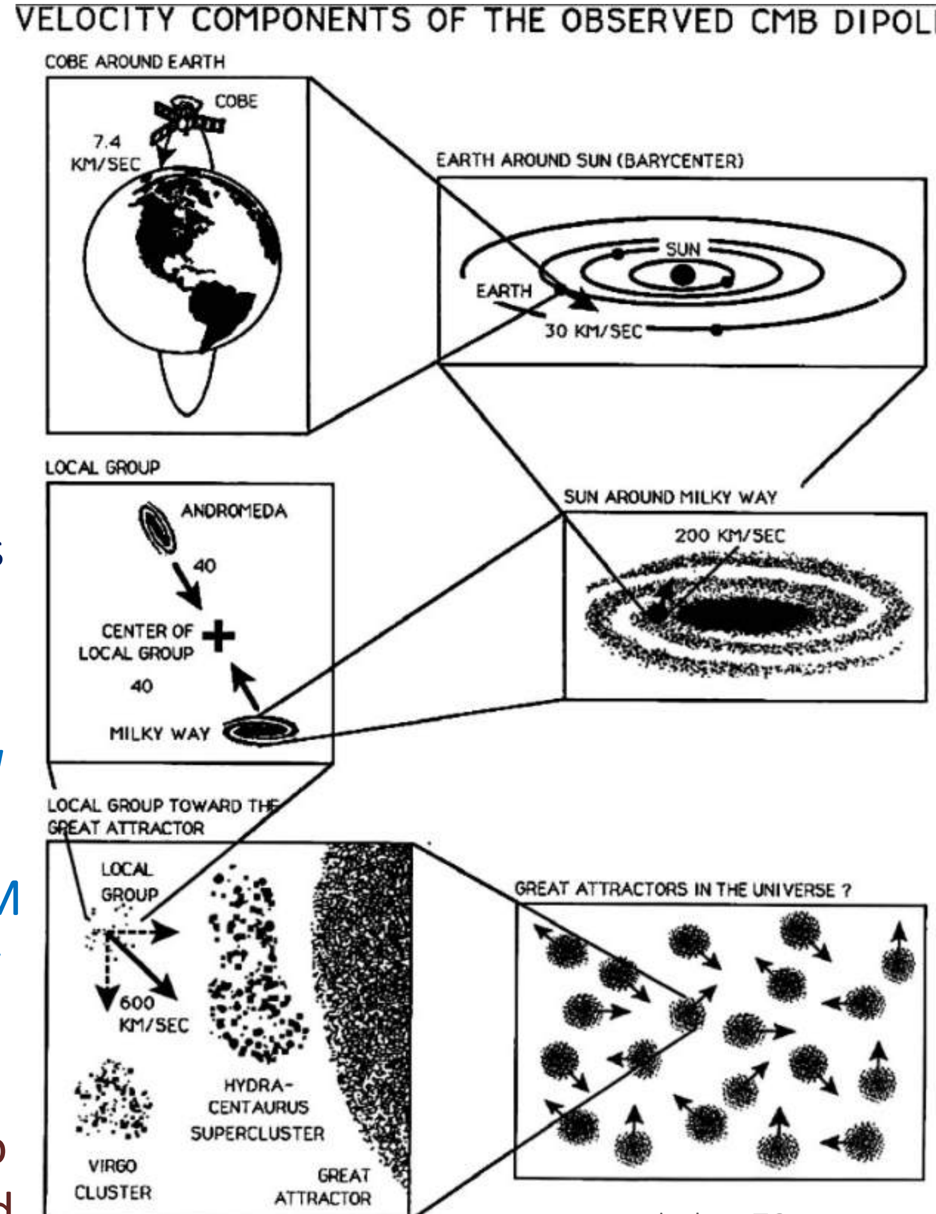


$$T(\theta) = \frac{T_0\sqrt{1-\beta^2}}{1-\beta\cos\theta}$$

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 Mpc

So all data is 'corrected' by transforming to the CMB frame - in which FLRW *should* hold



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

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 of the CP 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

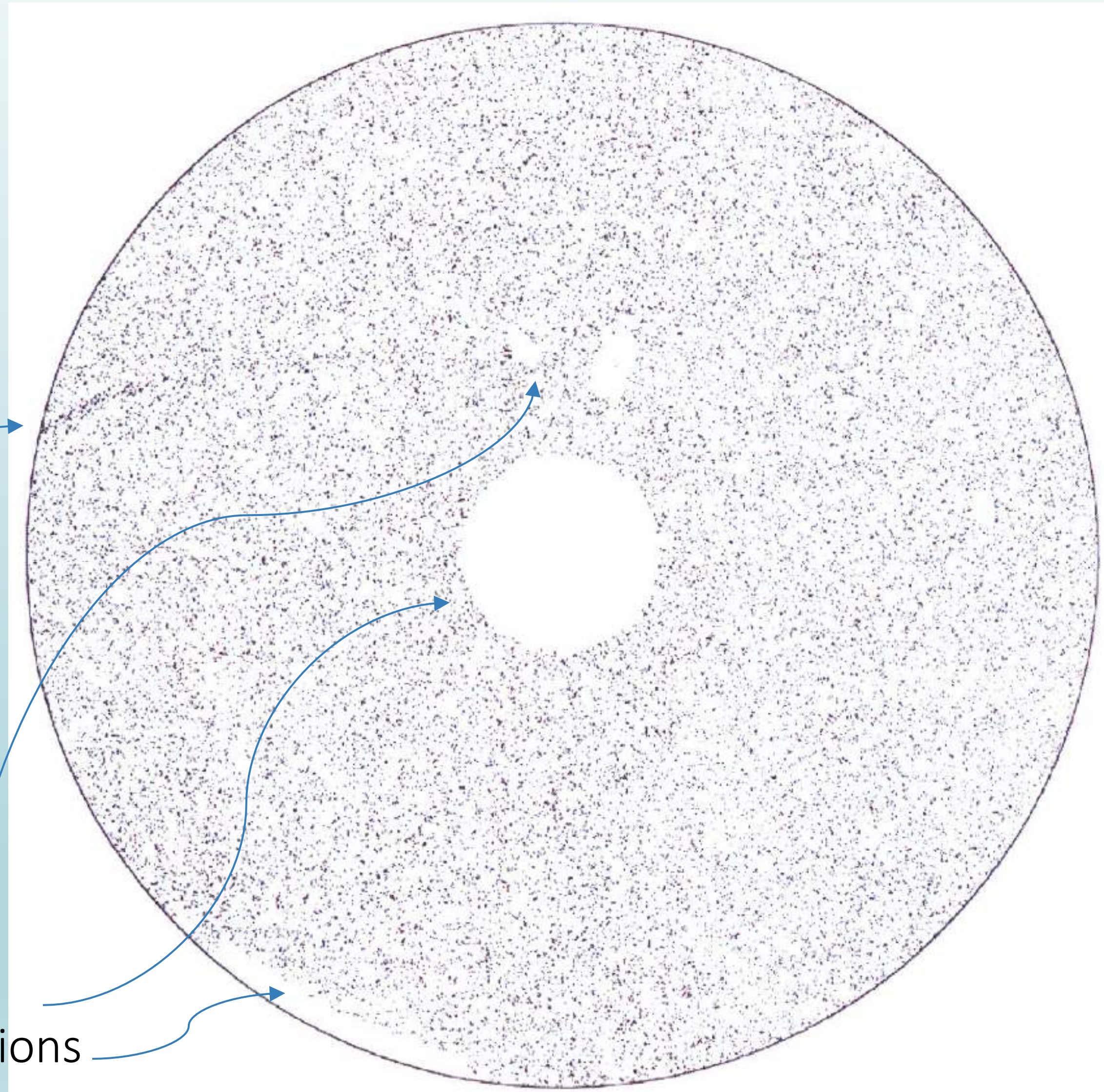
If the standards of rest determined by the MBR and the number counts were to be in serious disagreement, one would have to abandon

...

c) The standard FRW universe models

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

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



Milky Way

Unobserved regions

Peebles, *Principles of Physical Cosmology*, 1993

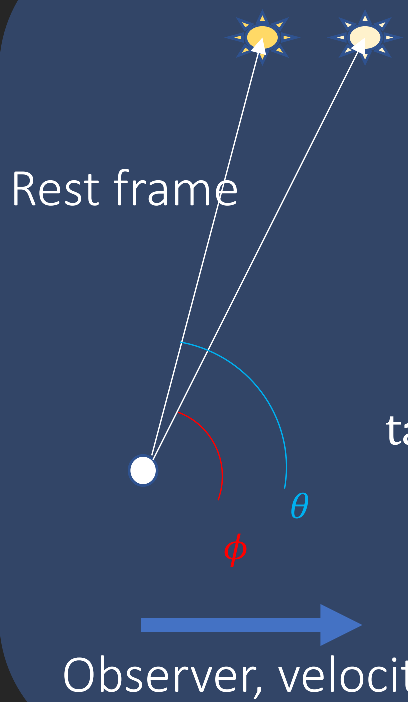
But if we are moving w.r.t. the cosmic rest frame, then distant sources *cannot* be isotropic!

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

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

Aberration

(Bradley 1727)



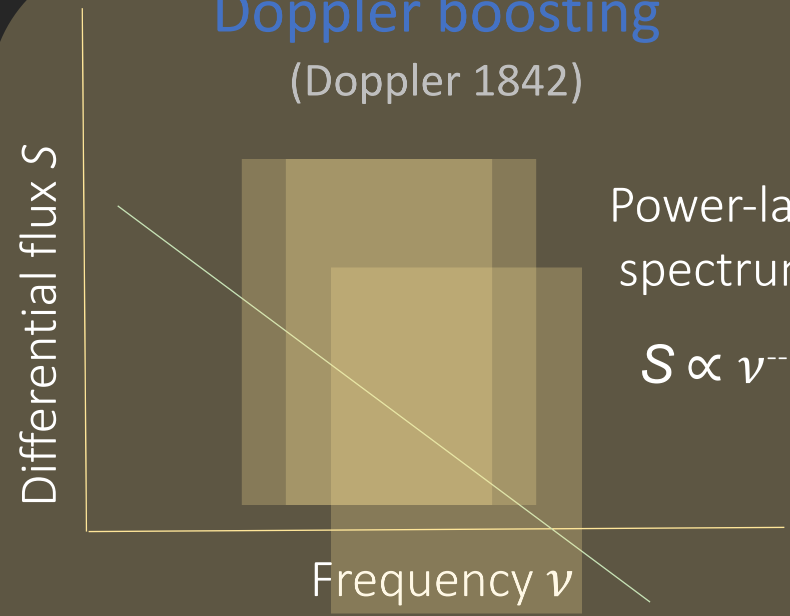
Moving frame

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

+

Doppler boosting

(Doppler 1842)



Power-law spectrum

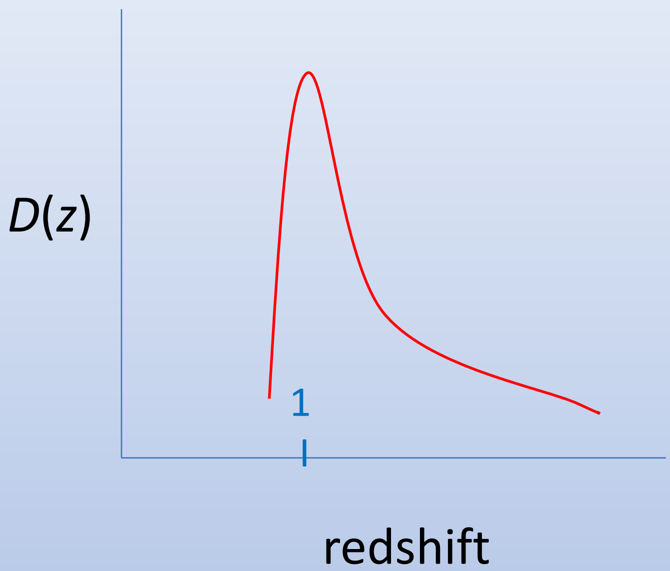
$S \propto \nu^{--\alpha}$

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 $<z> \sim 1$ (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, $<z> \sim 0.14$, $\vec{\mathcal{S}}\,(D(z))$ significant

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

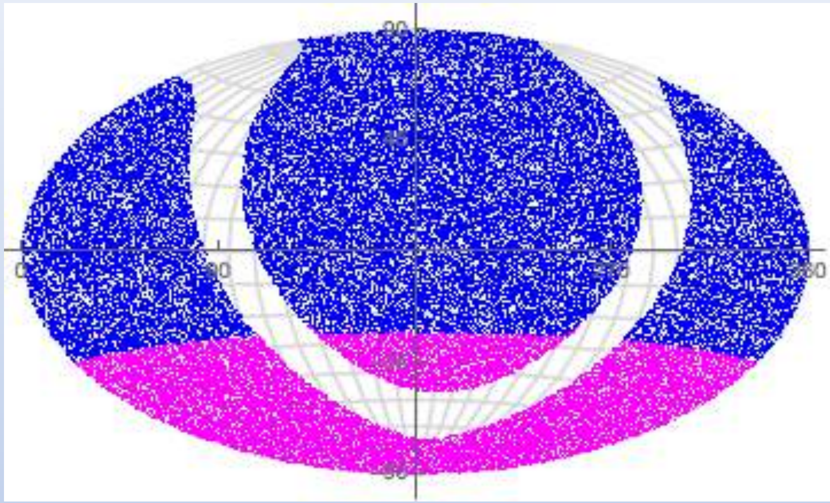
Wide Field Infrared Survey Explorer: 1,360,000 quasars, $<z> \sim 1.2$, $\vec{\mathcal{S}}\,(D(z)) \sim 1\%$

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°) (843 MHz survey at Dec < -30°)

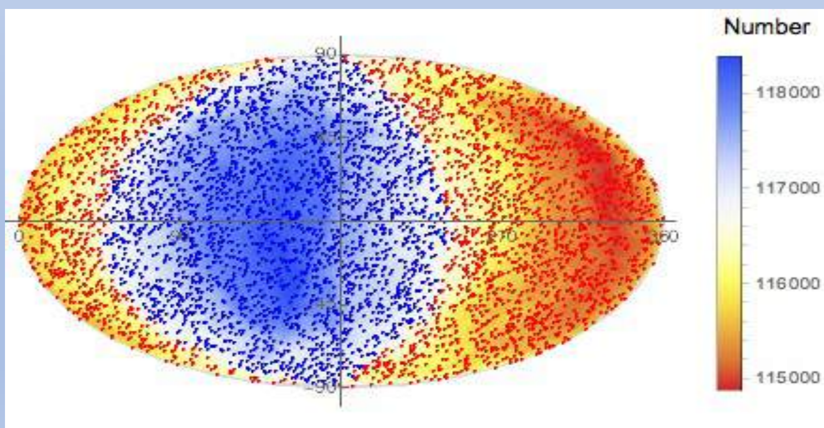
[Rescale the SUMSS fluxes by $(843\ \text{MHz}/1.4\ \text{GHz})^{-0.75} = 1.46$ to match with NVSS]

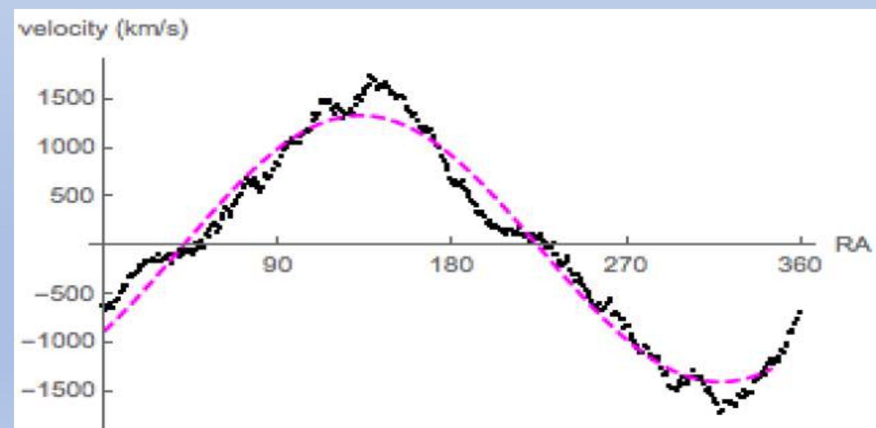


To get rid of any 'clustering dipole':

- Remove Galactic plane ±10°
  (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



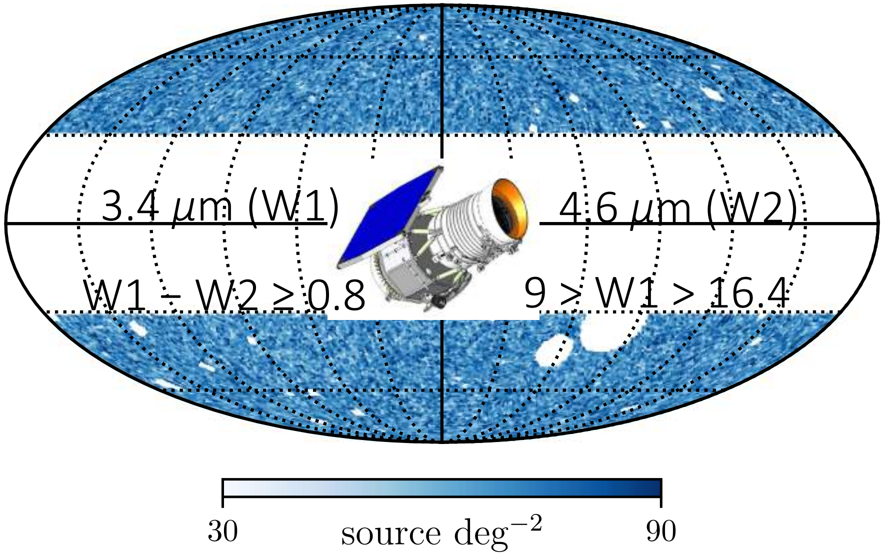


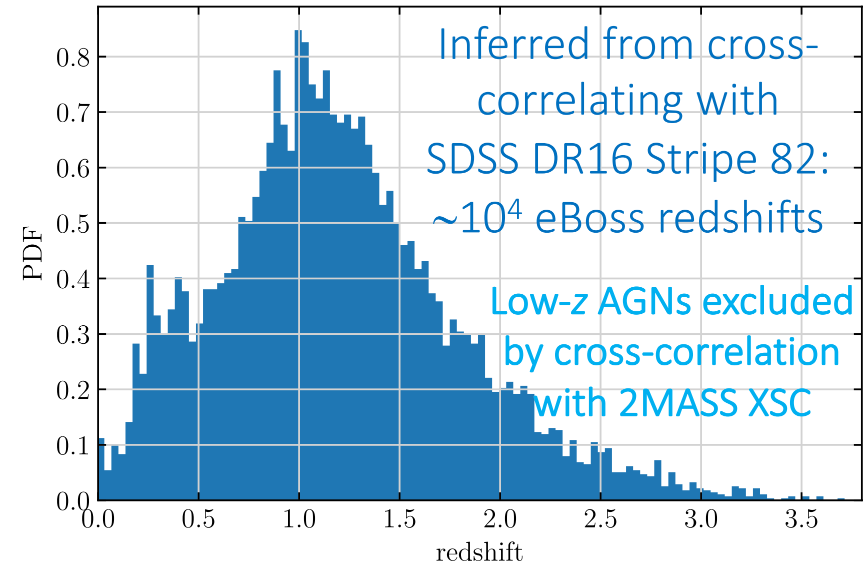
Confirms claim by Singal (ApJ **742**:L23,2011) … however source redshifts are not *directly* measured (also the statistical significance is only 2.8**σ** – by Monte Carlo)

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

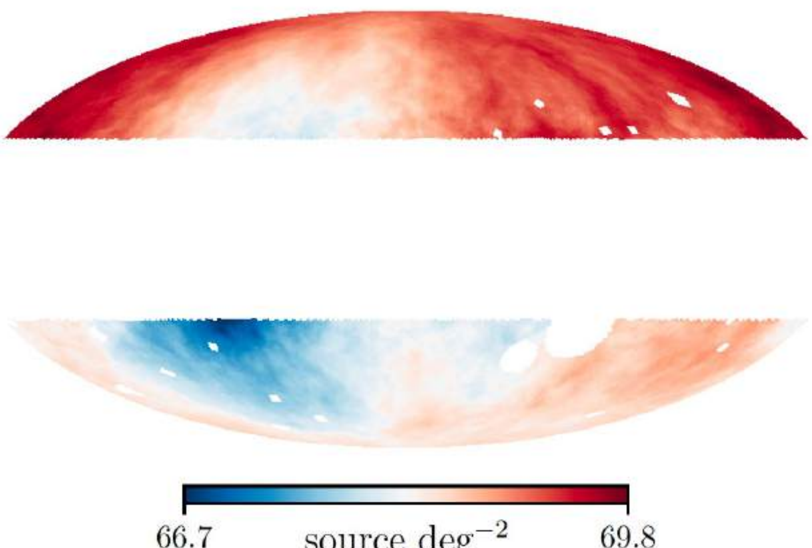
The CatWISE quasar catalogue

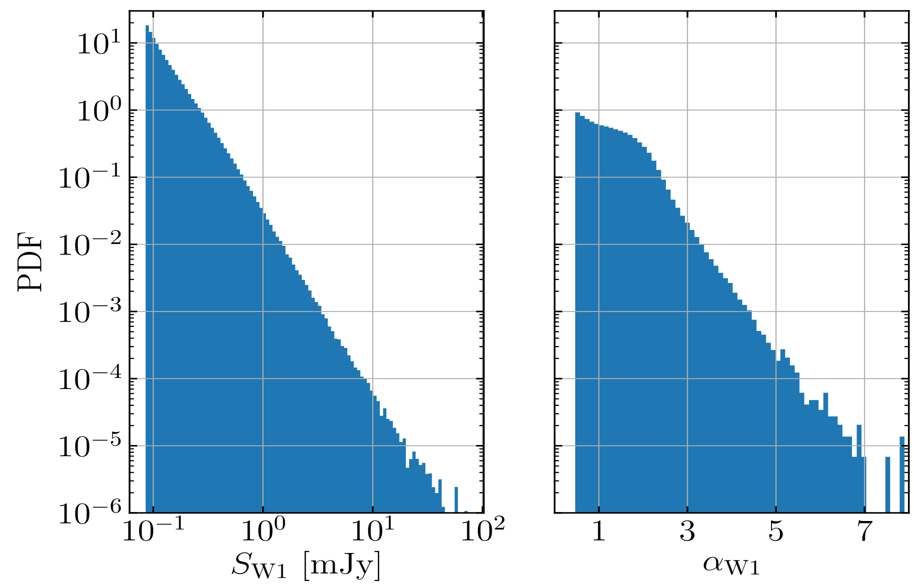
Secrest, Rameez, Von Hausegger, Mohayaee, S.S. & Colin, ApJL **908**:L51,2021





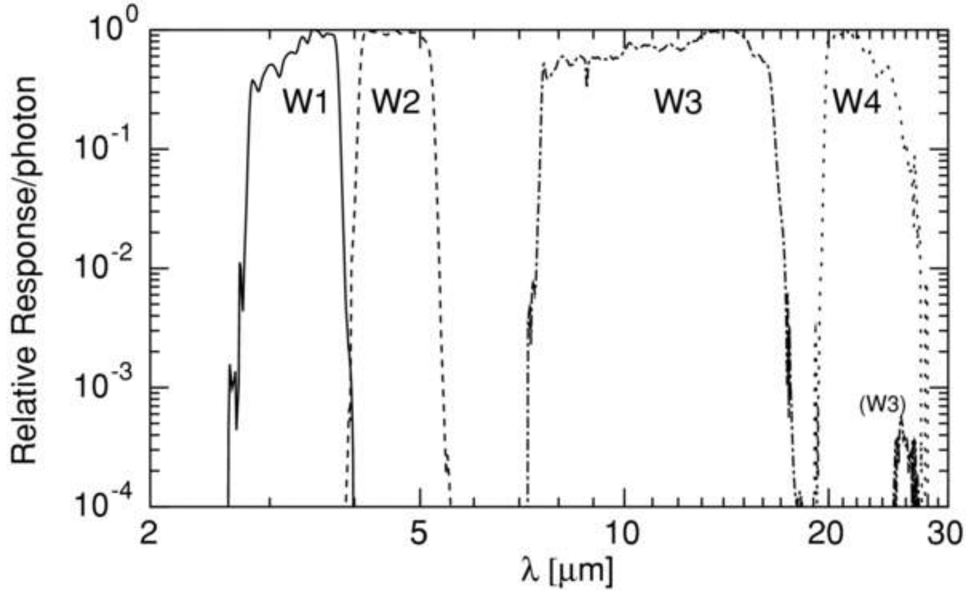
We now have a catalogue of 1.36 million quasars, with 99% at redshift > 0.1

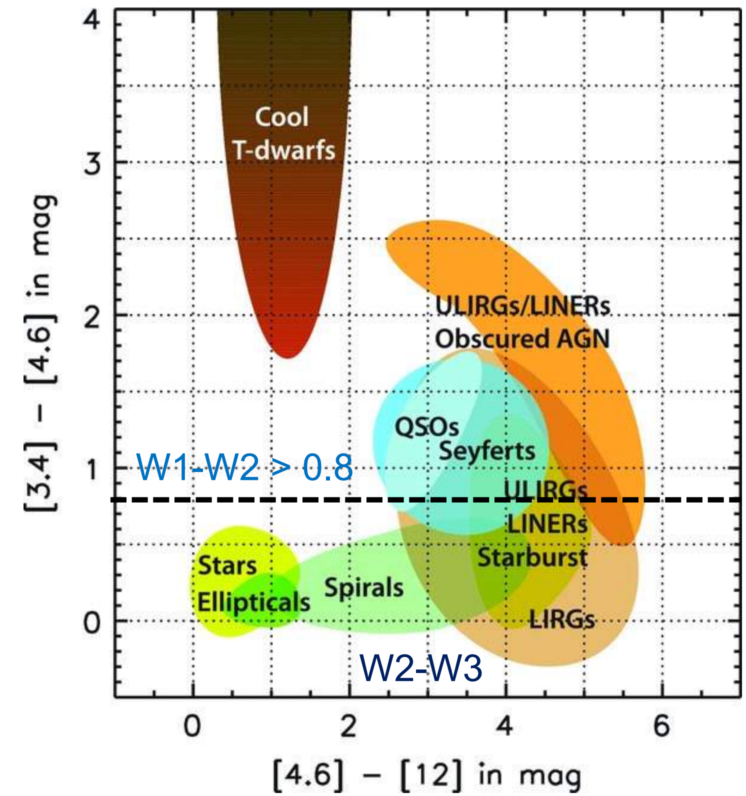




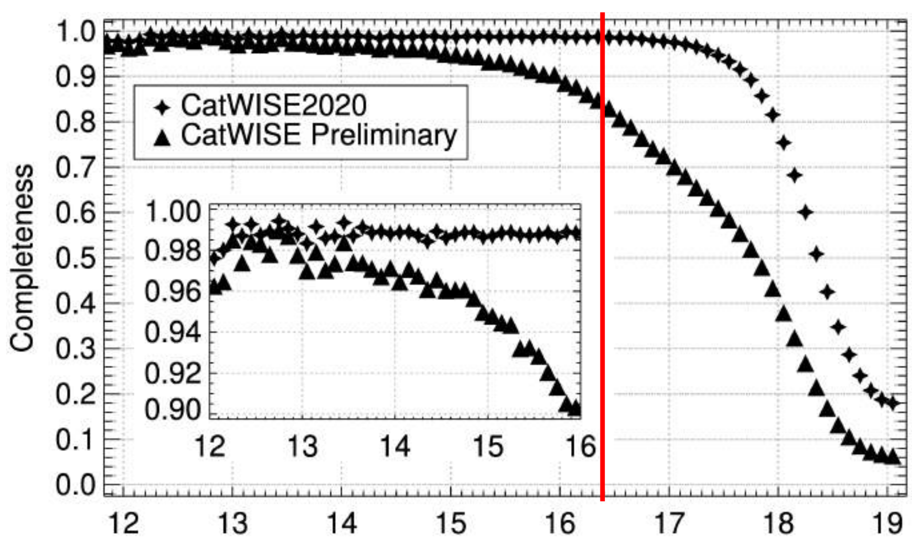
The dipole can be compared to that expected, knowing the spectrum & flux distribution

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

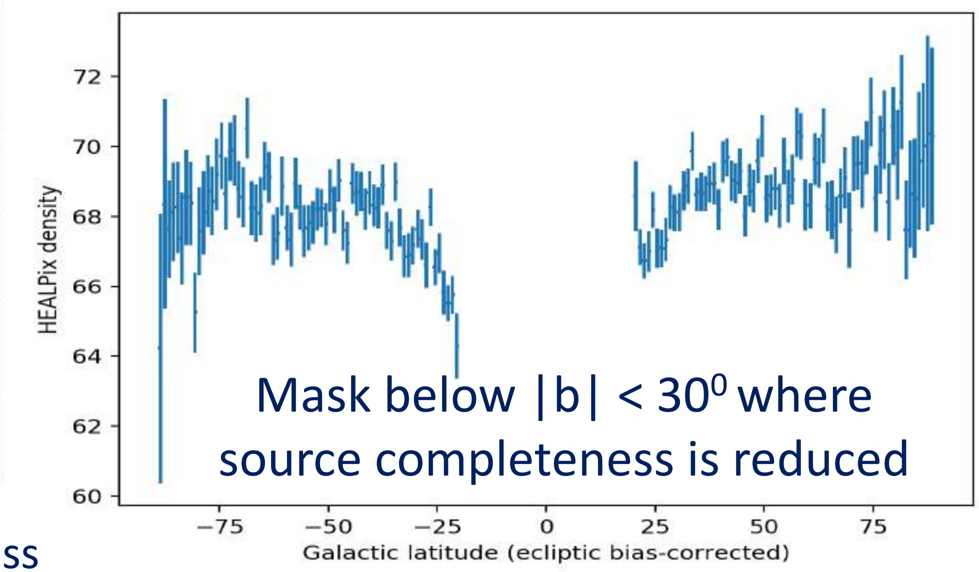




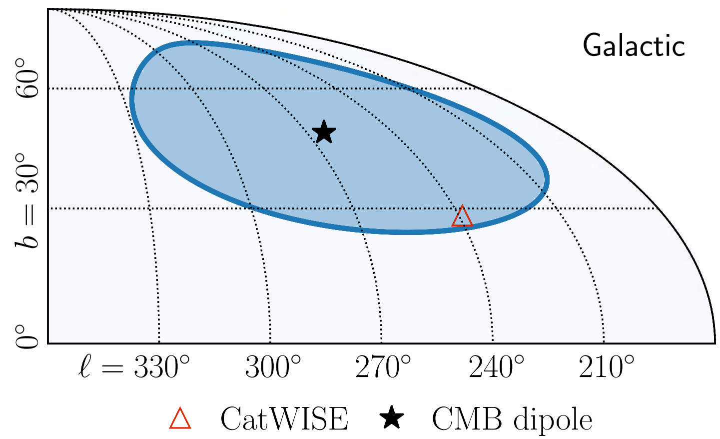
Wright *et al.*, AJ 140:1868,2010



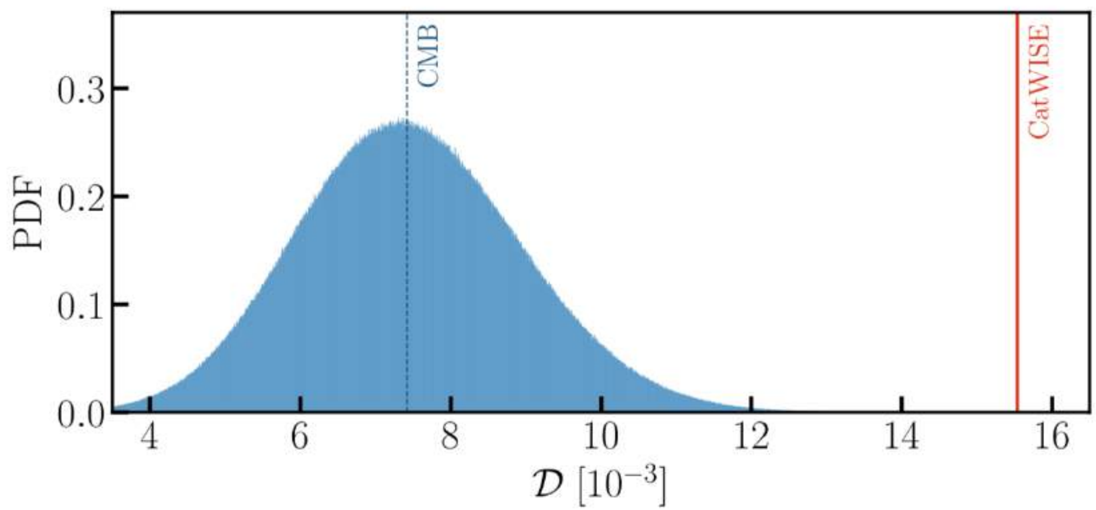
Magnitude cut W1 < 16.4 ensures completeness



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

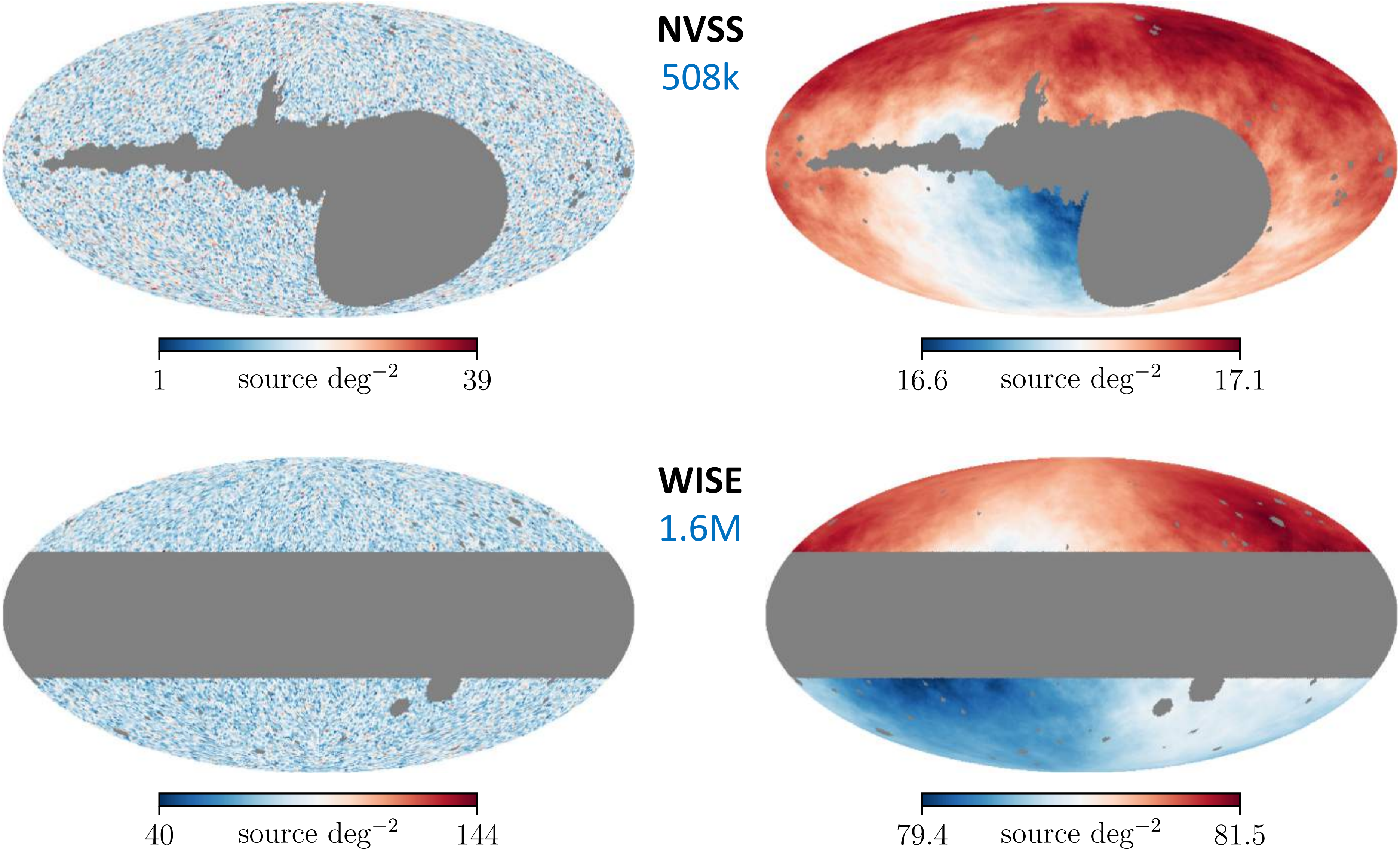


The kinematic interpretation of the CMB dipole is *rejected* with $p = 5 \times 10^{-7} \Rightarrow 4.9\sigma$

(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

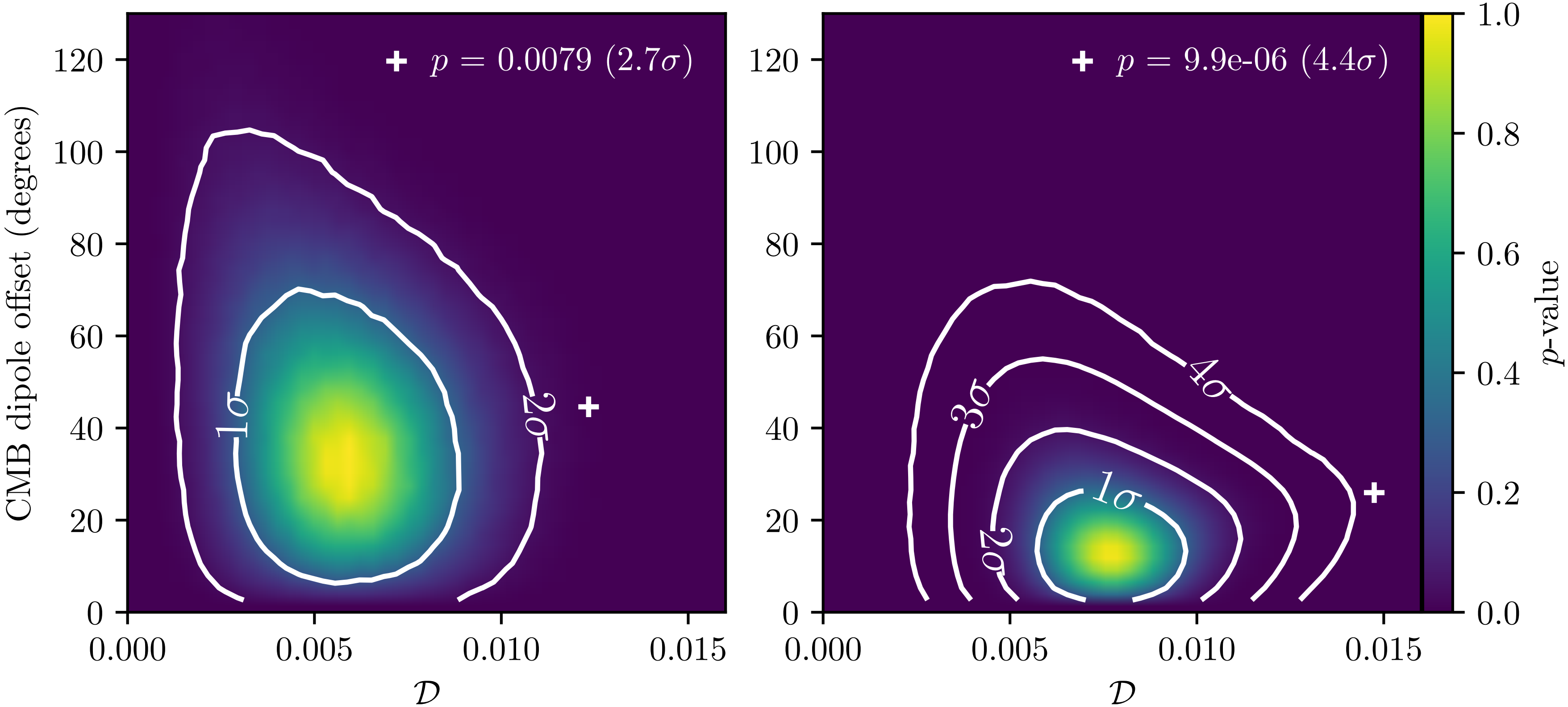


The two dipoles are *consistent* with each other; their vector mean is:

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

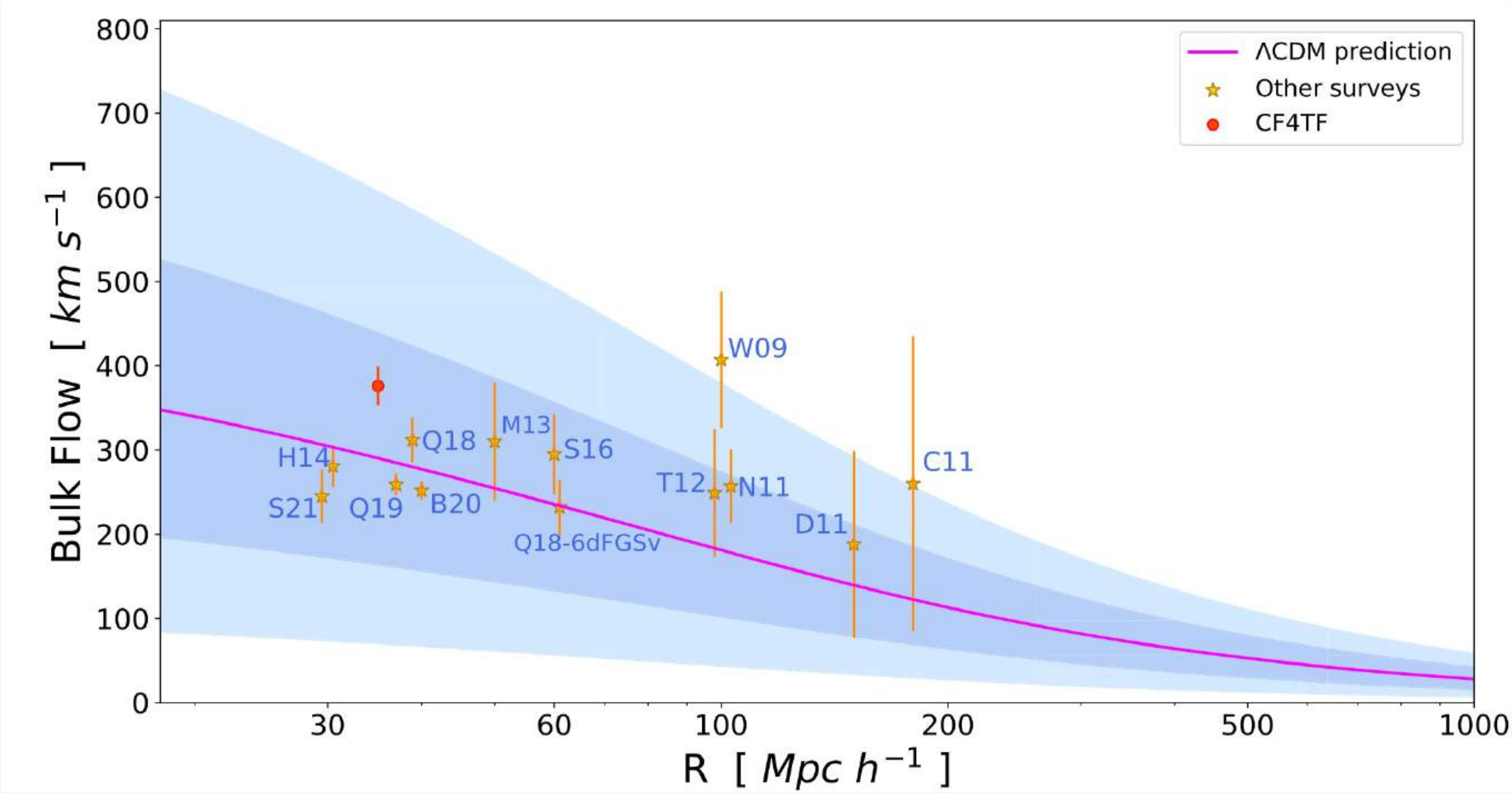


Distribution of CMB dipole offsets & kinematic dipole amplitudes of simulated null skies for NVSS (left) and WISE (right). Contours of equal *p*-value and equivalent σ are given (where the peak of the distribution corresponds to 0σ), with the found dipoles marked with + and their *p*-values are in the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

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

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

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.

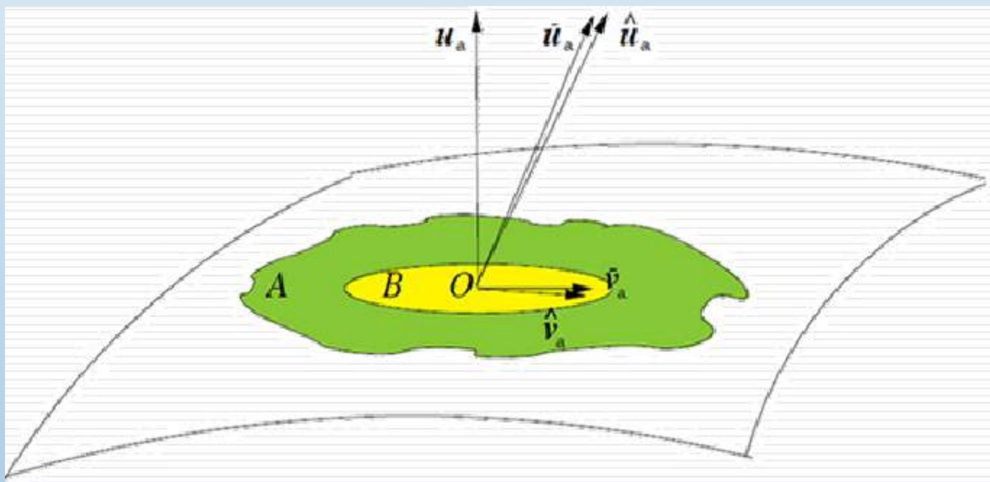
According to ΛCDM Hubble Volume simulations (e.g. 'Dark Sky'), *less than 1%* of Milky Way–like observers should experience a bulk flow as large as is observed, extending out as far as is seen.

So we are *not* typical 'Copernican' observers (Mohayaee, Rameez & S.S., arXiv: 2003.10420)

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

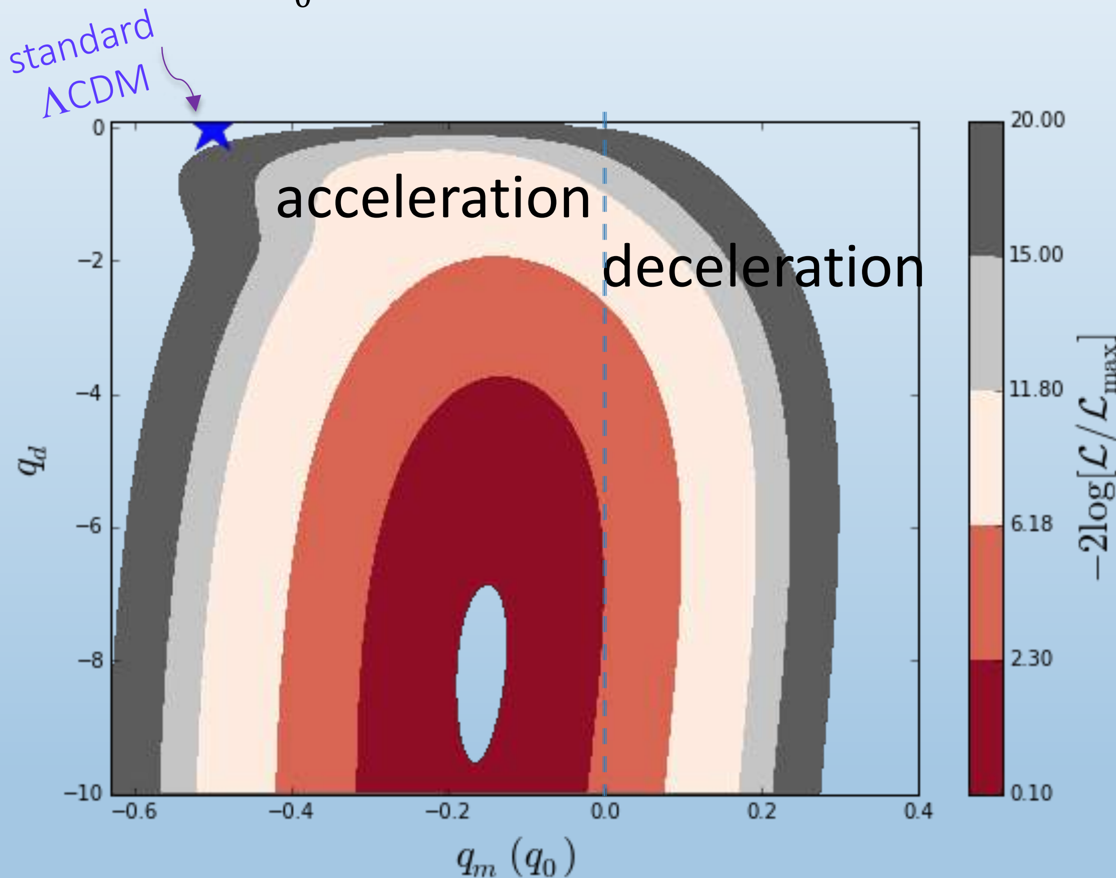
$$1 + \tilde{q} = (1 + q)\left(1 + \frac{\vartheta}{\Theta}\right)^{-2} - \frac{3\dot{\vartheta}}{\Theta^2}\left(1 + \frac{\vartheta}{\Theta}\right)^{-2},$$

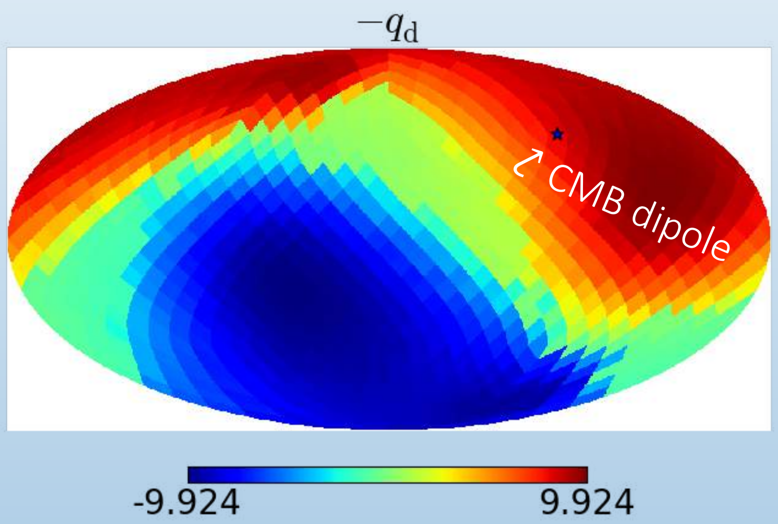
$$\tilde{\Theta} = \Theta + \vartheta,$$

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

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

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





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

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 ≠ the rest frame of the CMB

… This poses a serious challenge to the FLRW metric assumption

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

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

⇒ 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 the manifesto of Ellis & Stoeger, CQG 4:1697,1987 re. the 'fitting problem')