A challenge to the cosmological standard model

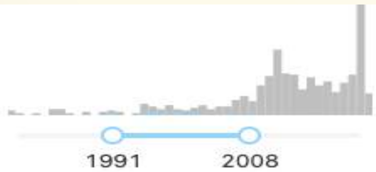
Subir Sarkar

Photo: Gabriel German

Dedicated to my dear mentor

Graham Ross (1944-2021)

Find a Ross, G.G. and Sarkar, S.



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- 10 authors or less — 8

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- Exclude Review of Particle Physics — 8

Document Type

- article — 8
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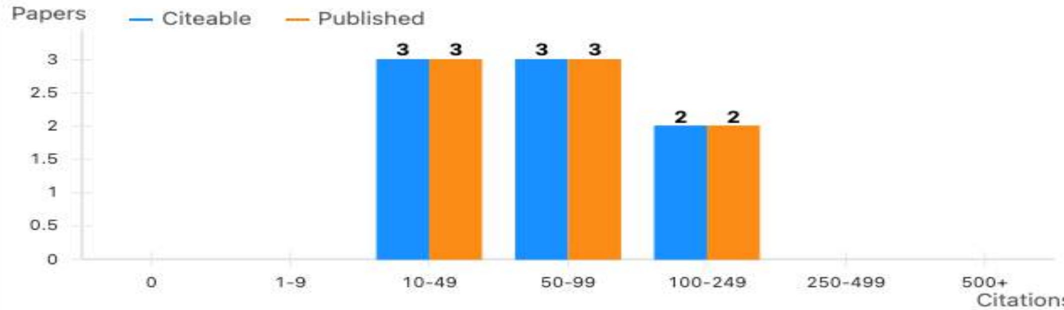


Fine tuning and the ratio of tensor to scalar density fluctuations from cosmological inflation ... no lower bound on r (grav. waves) #1
Shaun Hotchkiss (Oxford U., Theor. Phys.), Gabriel German (Oxford U., Theor. Phys.), Graham G. Ross (Oxford U., Theor. Phys.), Subir Sarkar (Oxford U., Theor. Phys.) (Apr, 2008)
Published in: *JCAP* 10 (2008) 015 • e-Print: 0804.2634 [astro-ph]
pdf DOI cite claim 19 citations

Racetrack inflation and assisted moduli stabilisation ... no overshoot #2
Zygmunt Lalak (CERN and Warsaw U.), Graham G. Ross (CERN and Oxford U., Theor. Phys.), Subir Sarkar (Oxford U., Theor. Phys.) (Mar, 2005)
Published in: *Nucl.Phys.B* 766 (2007) 1-20 • e-Print: hep-th/0503178 [hep-th]
pdf links DOI cite claim 63 citations

Low scale inflation ... inflation is possible down to EW scale #3
Gabriel German (Mexico U., Cuernavaca), Graham G. Ross (Oxford U.), Subir Sarkar (Oxford U.) (Mar, 2001)
Published in: *Nucl.Phys.B* 608 (2001) 423-450 • e-Print: hep-ph/0103243 [hep-ph]
pdf DOI cite claim 96 citations

Implementing quadratic supergravity inflation ... 'hilltop inflation' #4
Gabriel German (Oxford U.), Graham G. Ross (Oxford U.), Subir Sarkar (Oxford U.) (Aug, 1999)
Published in: *Phys.Lett.B* 469 (1999) 46-54 • e-Print: hep-ph/9908380 [hep-ph]
pdf DOI cite claim 39 citations

Multiple inflation ... SUGRA flat directions as 'waterfall fields' #5
Jennifer A. Adams (Uppsala U.), Graham G. Ross (Oxford U.), Subir Sarkar (Oxford U.) (Apr, 1997)
Published in: *Nucl.Phys.B* 503 (1997) 405-425 • e-Print: hep-ph/9704286 [hep-ph]
pdf DOI cite claim 197 citations

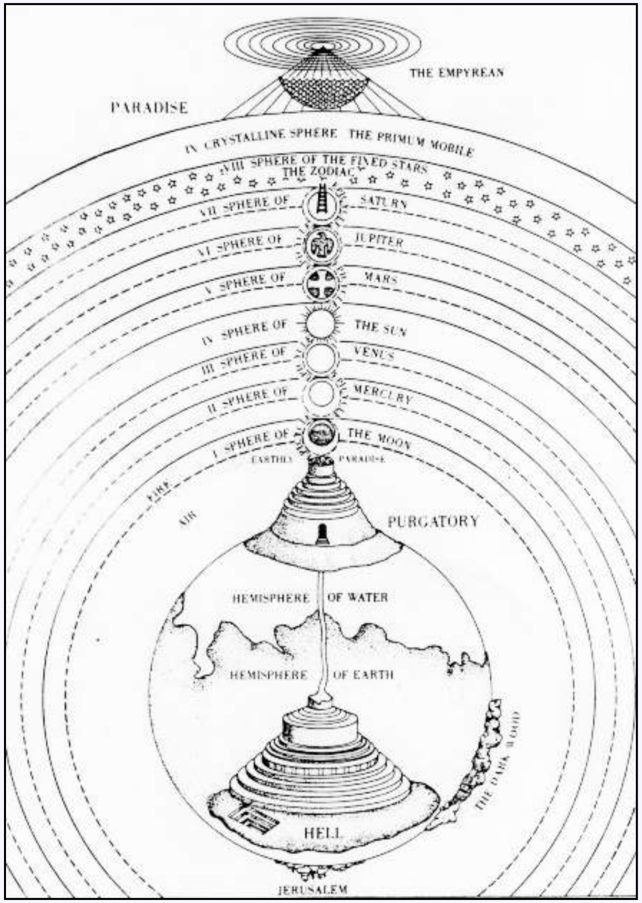
Natural supergravity inflation ... inflaton as a Goldstone mode #6
Jennifer A. Adams (Uppsala U.), Graham G. Ross (Oxford U.), Subir Sarkar (Oxford U.) (Aug, 1996)
Published in: *Phys.Lett.B* 391 (1997) 271-280 • e-Print: hep-ph/9608336 [hep-ph]
pdf DOI cite claim 65 citations

Successful supersymmetric inflation ... Showed that $H_{infl} < m_{3/2}$ #7
Graham G. Ross (CERN), Subir Sarkar (Oxford U.) (Jun, 1995)
Published in: *Nucl.Phys.B* 461 (1996) 597-624 • e-Print: hep-ph/9506283 [hep-ph]
pdf DOI cite claim 110 citations

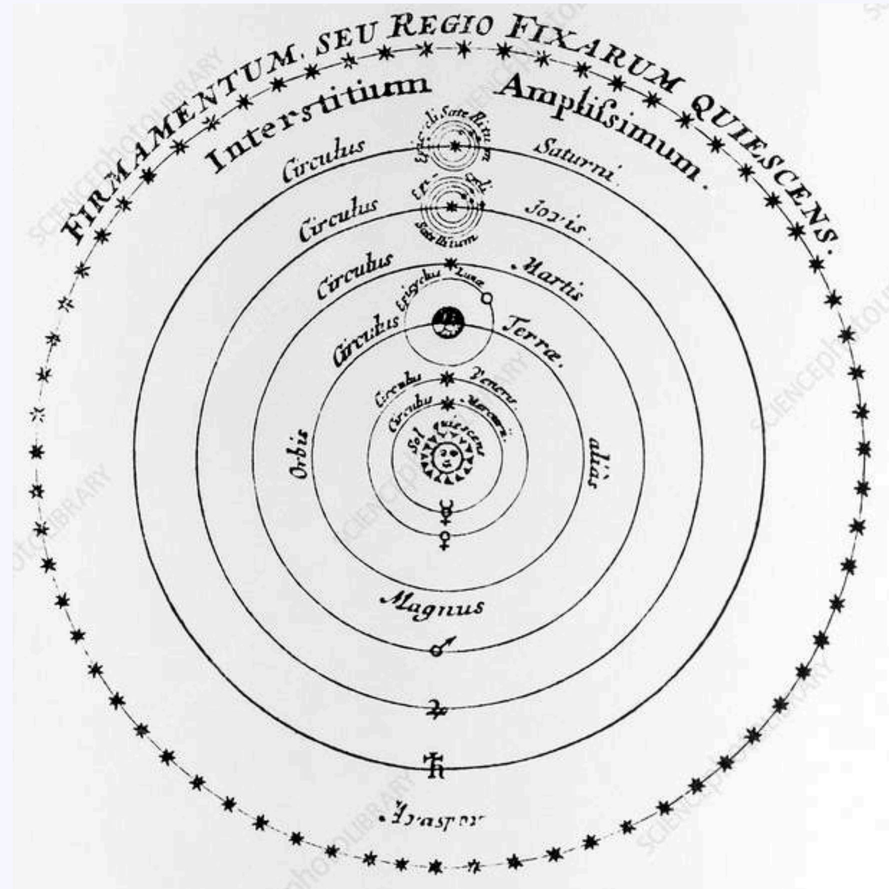
On the implications of a 17-keV neutrino ... unlikely to exist #8
A. Hime (Oxford U.), R.J.N. Phillips (Rutherford), Graham G. Ross (Oxford U.), Subir Sarkar (Oxford U.) (Feb, 1991)
Published in: *Phys.Lett.B* 260 (1991) 381-388
DOI cite claim 22 citations

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



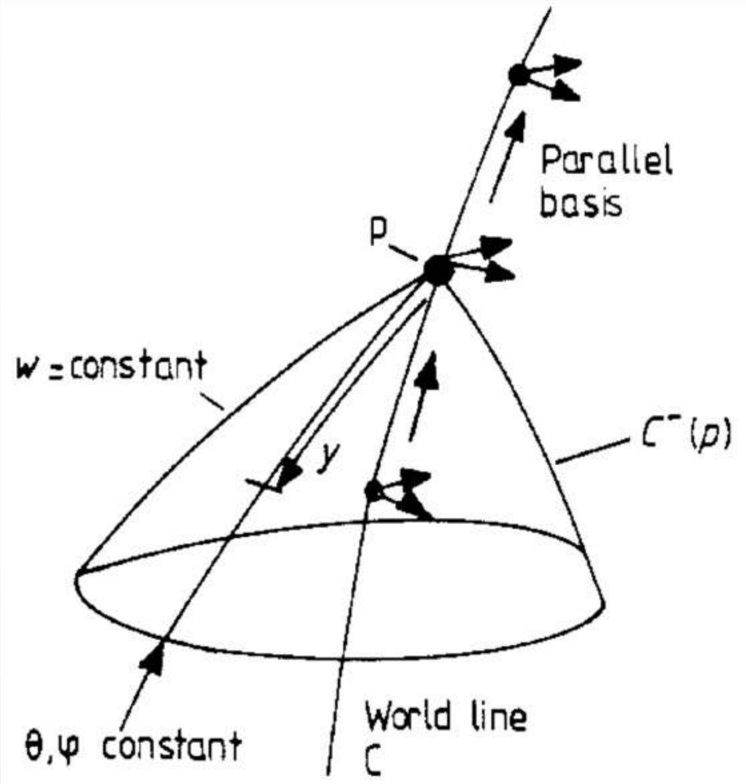
Aristotle … Ptolemy → The Divine Comedy, Dante Allighieri (1321)



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 …

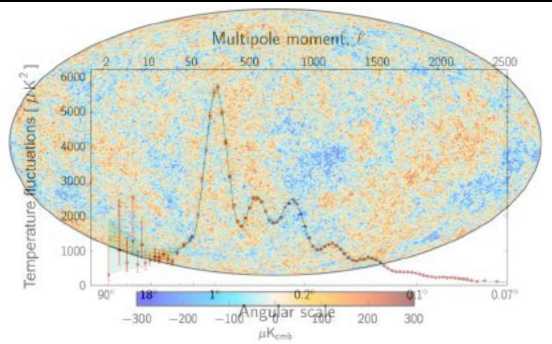
All we can learn about the universe is contained within our past light cone



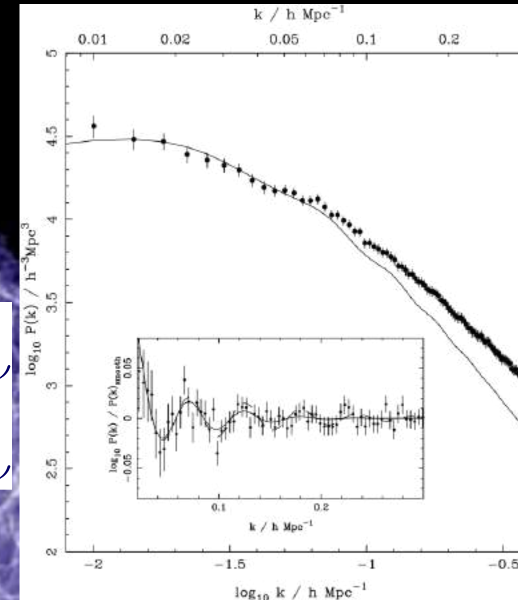
Ellis & Stoeger, CQG 4:1697,1987

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)



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



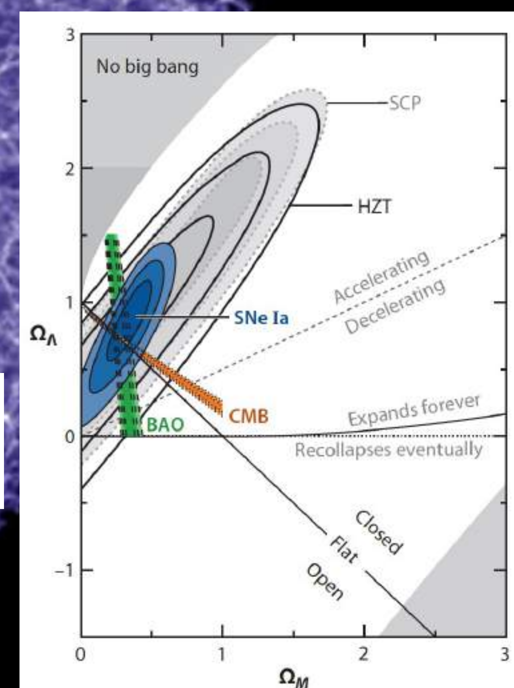
$$T_{\mu\nu} = -\langle\rho\rangle_{\text{fields}}\ g_{\mu\nu}$$
$$\Lambda = \lambda + 8\pi G_{\rm N}\langle\rho\rangle_{\text{fields}}$$

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

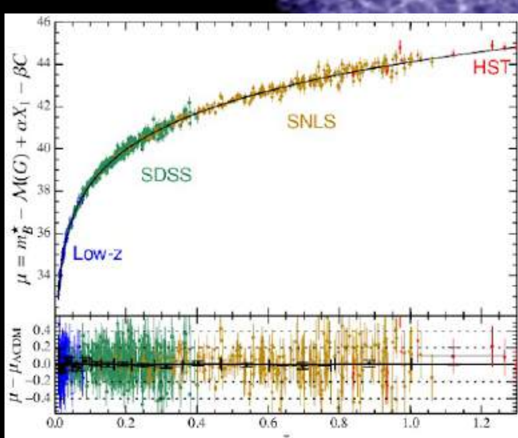
$$\Rightarrow H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G_{\rm N}\rho_{\rm m}}{3} - \frac{k}{a^2} + \frac{\Lambda}{3}$$
$$\equiv {H_0}^2\left[\Omega_{\rm m}(1+z)^3 + \Omega_k(1+z)^2 + \Omega_\Lambda\right]$$

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

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



$$\Omega_{\rm m} + \Omega_{\rm k} + \Omega_\Lambda = 1$$

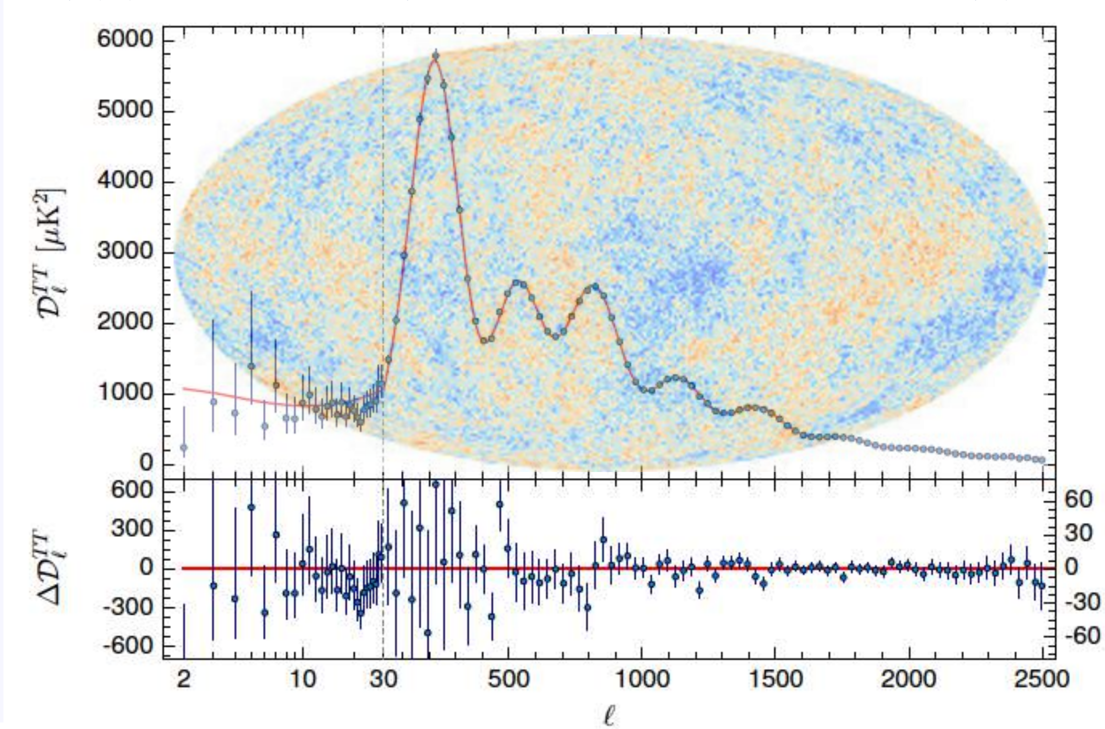


$0.8\Omega_{\rm m}$ - $0.6\Omega_\Lambda \approx$ -0.2 (SNe Ia),
$\Omega_{\rm k} \approx 0.0$ (CMB), $\Omega_{\rm m} \sim 0.3$ (Clusters, BAO)

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

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

CMB data is well-fit by the 6-param. ΛCDM model + power-law $P(\kappa)$



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

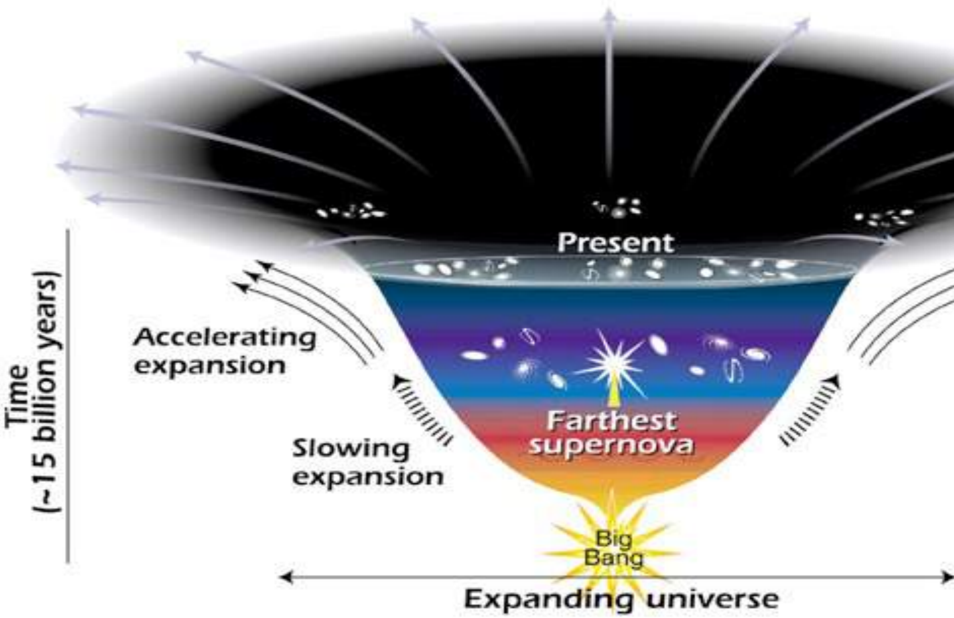
But there is no entry for Λ

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

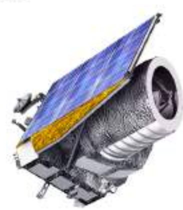
(To detect the late-ISW correlations between CMB & structure induced by Λ will require 10 million redshifts)

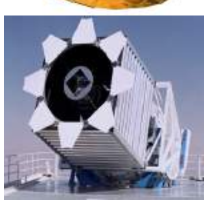
It is the Cosmic Sum sum rule that is used to *infer* a non-zero Λ of $O(H_0^2)$ from observations of SNe Ia, CMB, BAO, lensing etc …

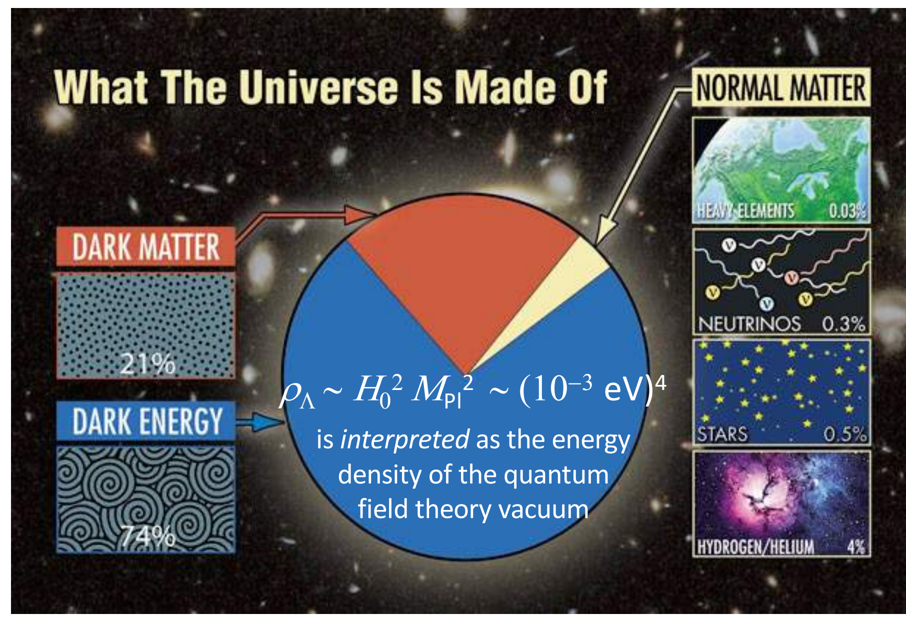
There is as yet no compelling *dynamical* evidence for Λ (e.g. the late-ISW effect)



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`

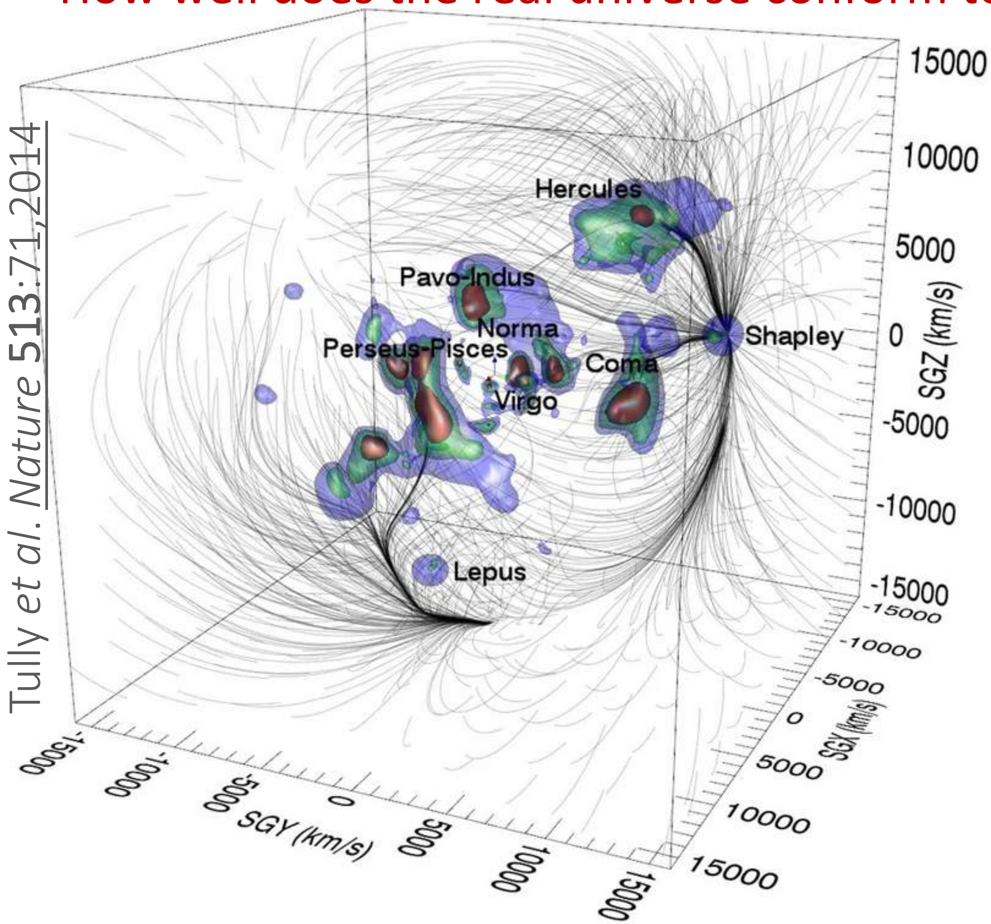






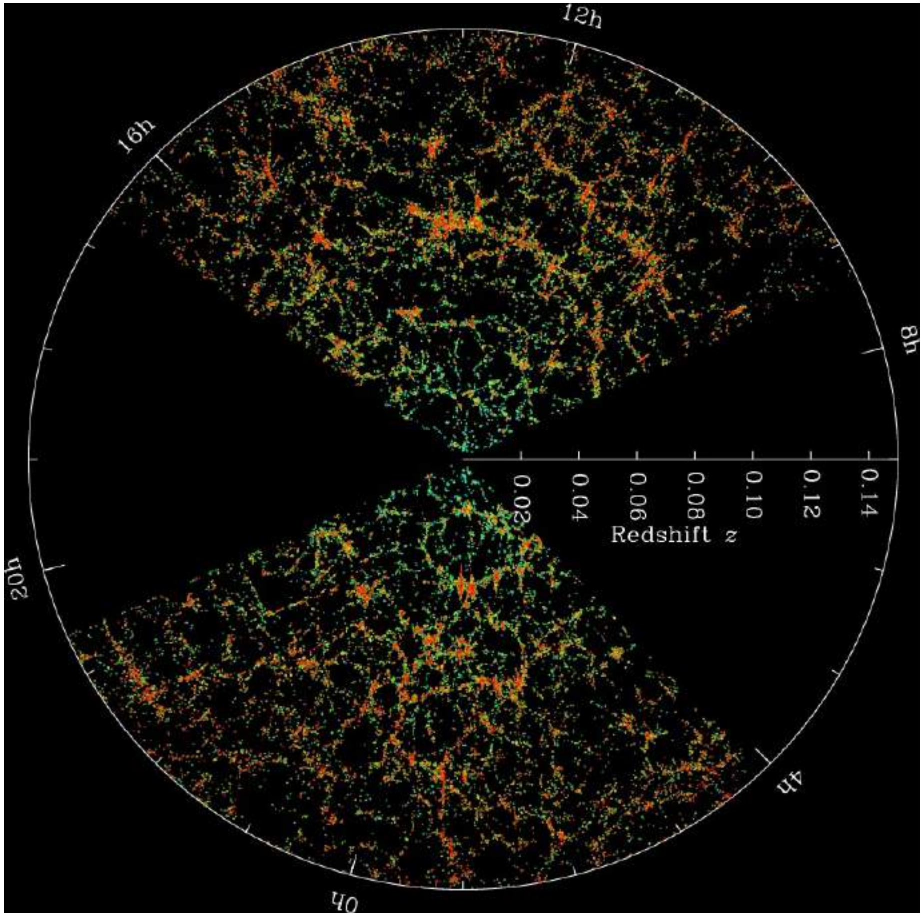
There has been substantial investment in major satellites and telescopes to *measure the parameters* of this standard cosmological model with increasing precision … but surprisingly little work on ***testing its foundational assumptions***

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



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?

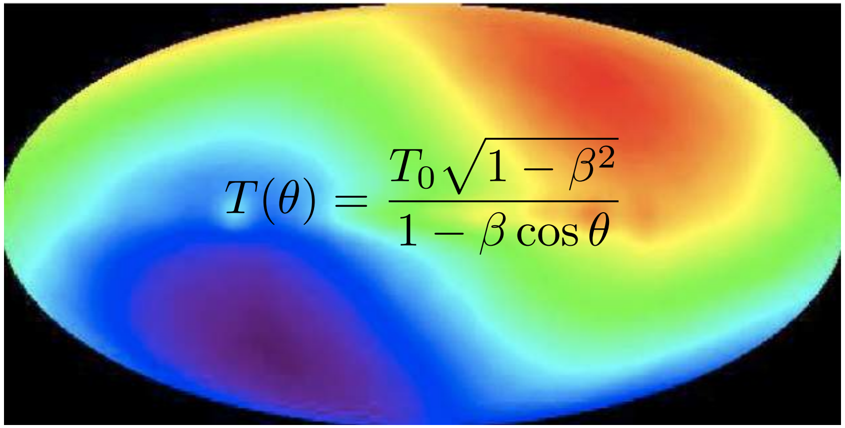
… To assume that we are a '*typical*' observer?

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

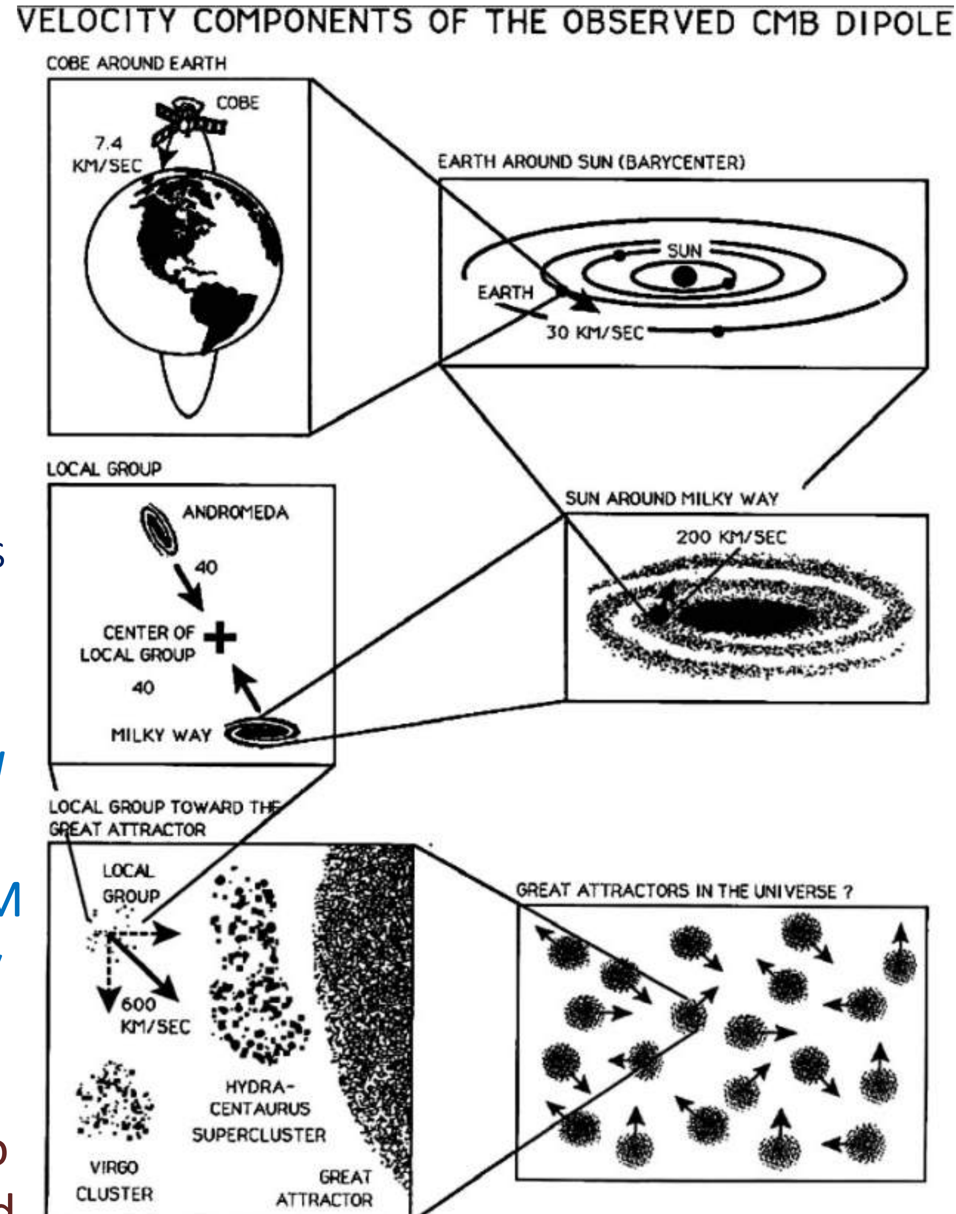
Stewart & Sciama *Nature* **216**:748,1967
Peebles & Wilkinson, *PRL* **174**:2168,1968

THE UNIVERSE IS *NOT* ISOTROPIC AROUND US

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



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



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

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

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)

A TEST WAS PROPOSED AFTER COSMOLOGICALLY DISTANT RADIO SOURCES WERE OBSERVED

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

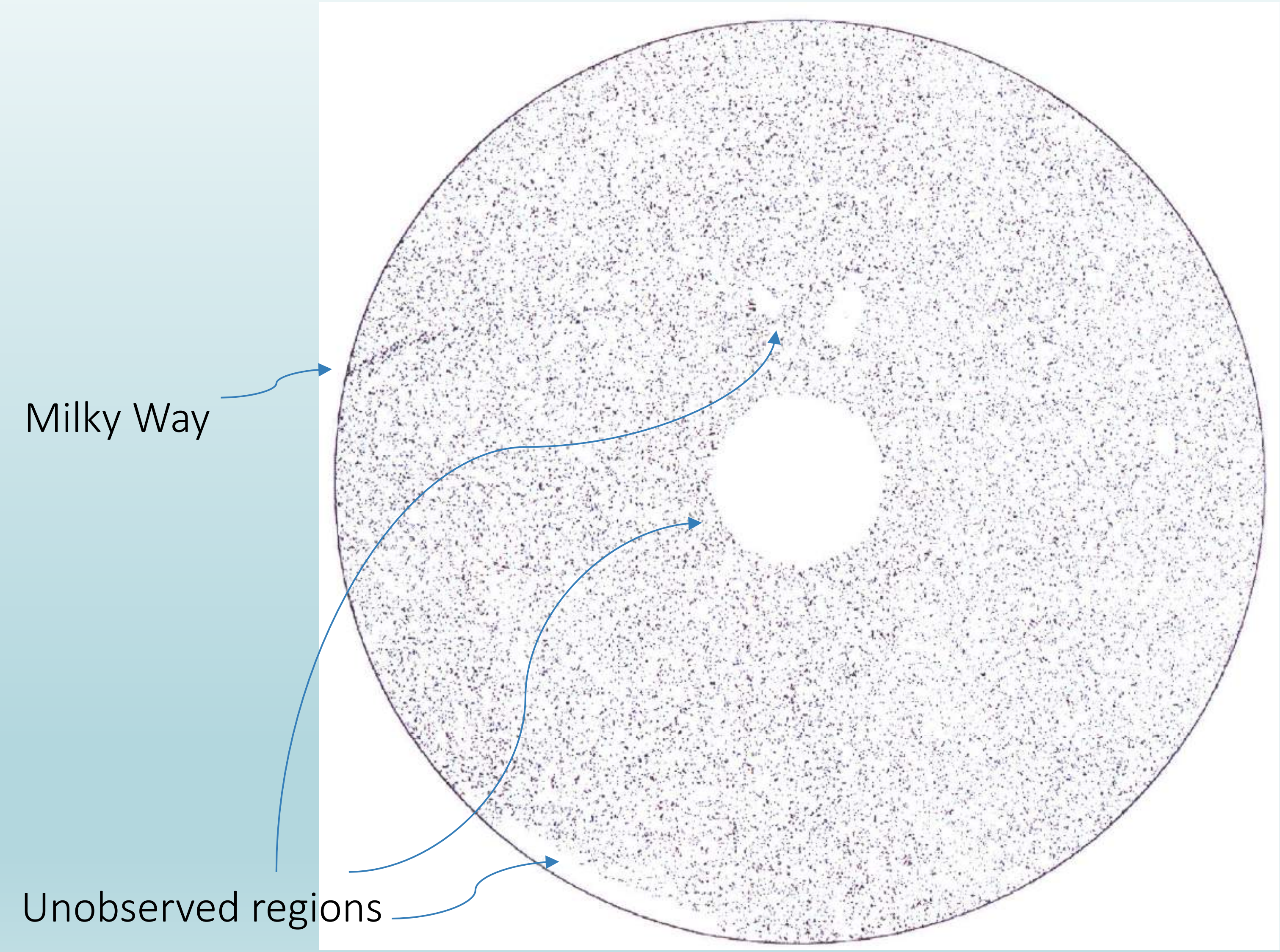
If the standards of rest determined by the MBR and the number counts were to be in serious disagreement, one would have to abandon

...

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



Peebles, *Principles of Physical Cosmology*, 1993

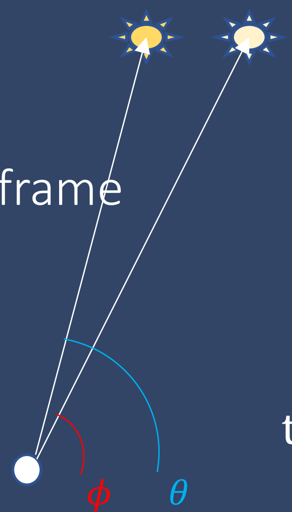
But if we are moving w.r.t. the cosmic rest frame, then distant sources *cannot* be isotropic!

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)



Moving frame

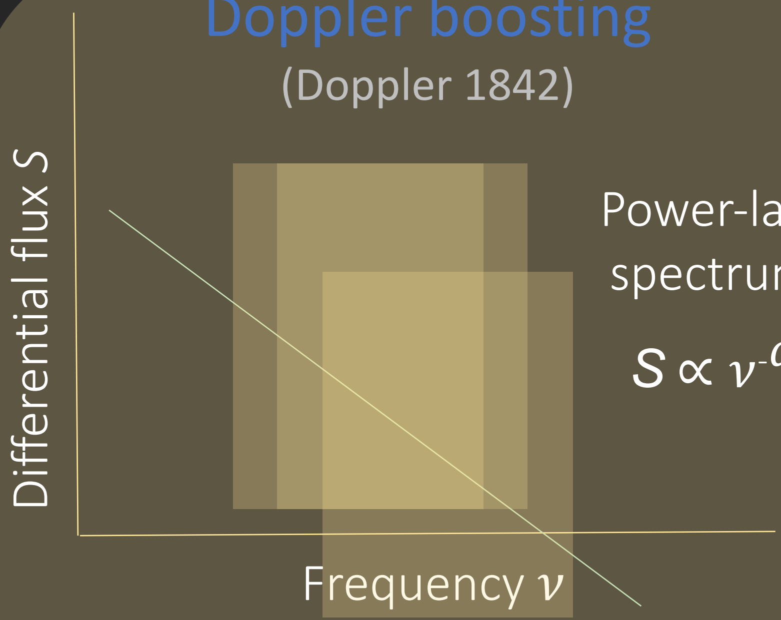
$$\tan\phi = \frac{\sin\theta}{\gamma(\cos\theta + \frac{v}{c})}$$

Observer, velocity $\boldsymbol{v}$

+

Doppler boosting

(Doppler 1842)



Power-law spectrum

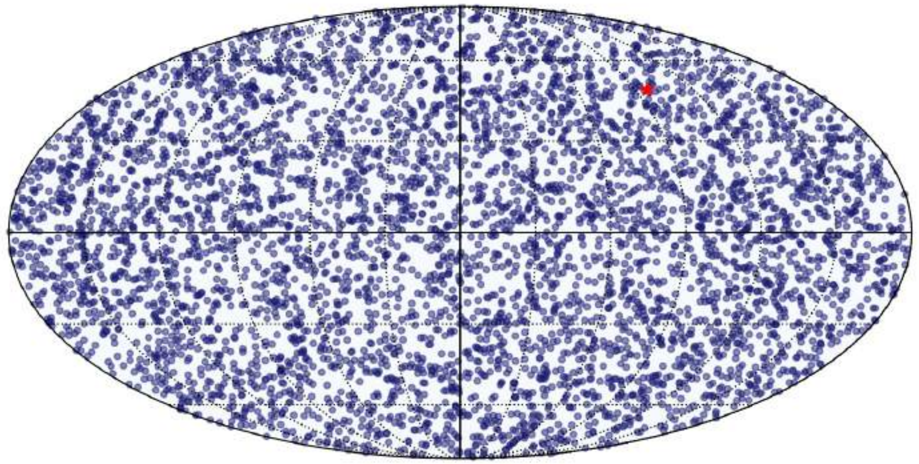
$S \propto \nu^{-\alpha}$

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

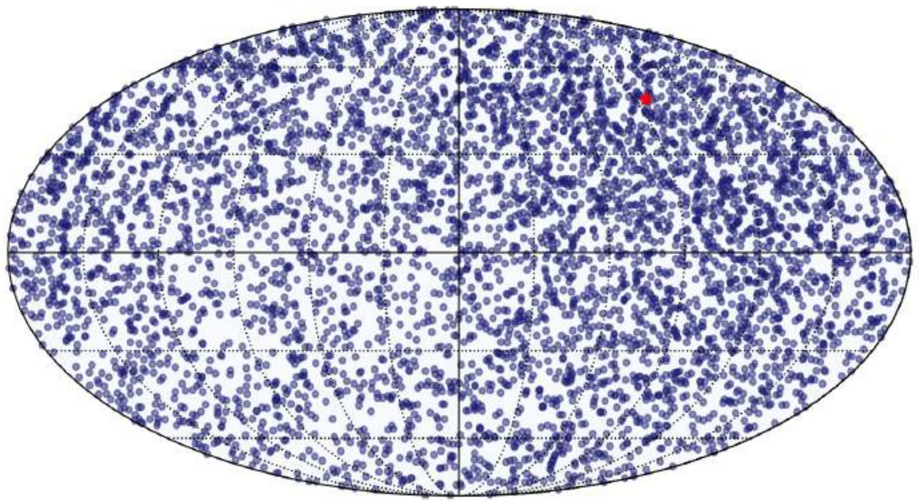
Flux-limited catalogue ➞ *more* sources in direction of motion

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

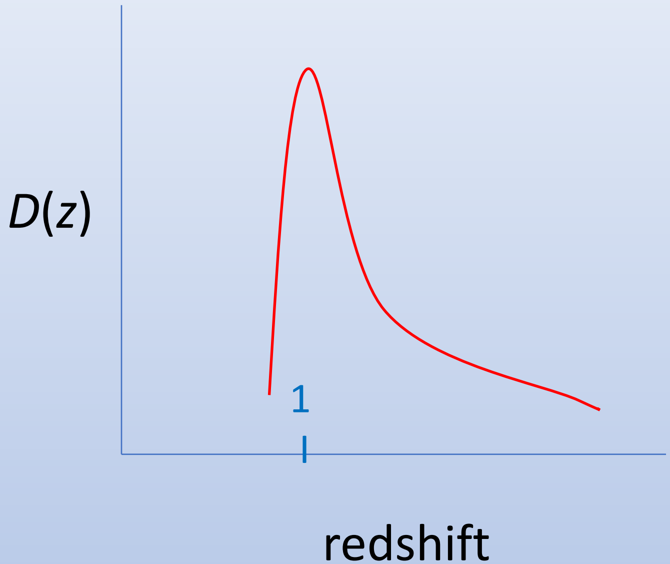
Galaxies / quasars in CMB "rest frame"



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



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

$\vec{\mathcal{K}} \rightarrow$ 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.), $\vec{\mathcal{S}}\,(D(z)) \rightarrow 0$ (est.)

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

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

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

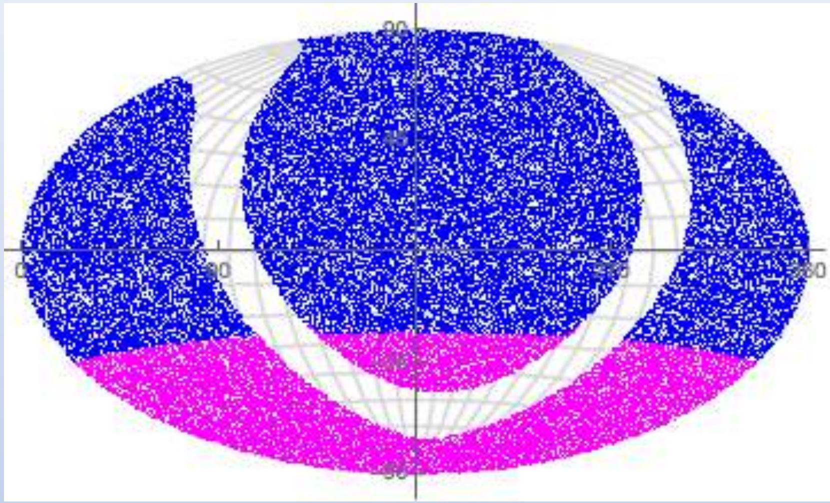
Wide Field Infrared Survey Explorer: 1,360,000 quasars, <*z*> ~ 1.2, $\vec{\mathcal{S}}\,(D(z)) \sim 1\%$

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°)

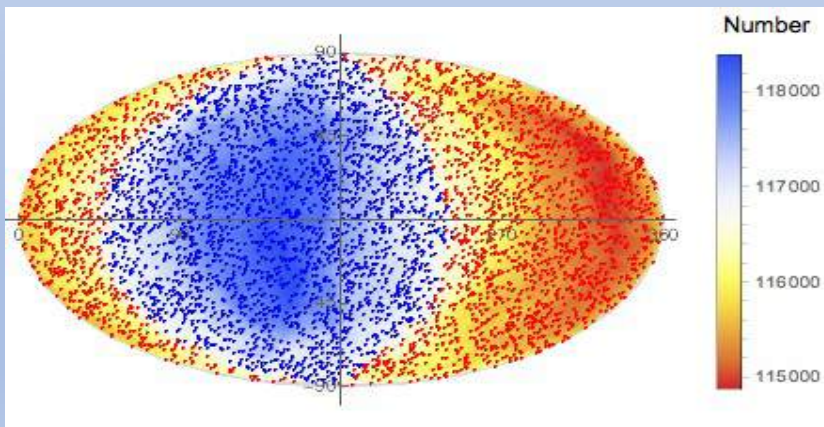
[Rescale the SUMSS fluxes by $(843 \text{ MHz}/1.4 \text{ GHz})^{-0.75} = 1.46$ to match with NVSS]

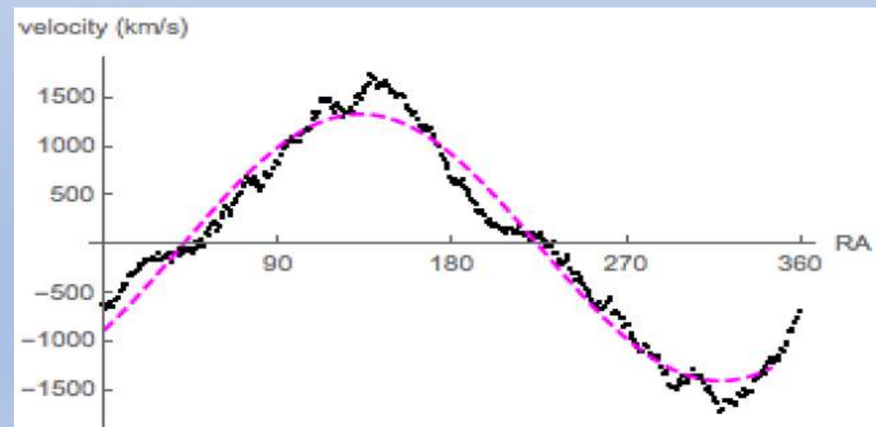


To get rid of any 'clustering dipole':

- 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



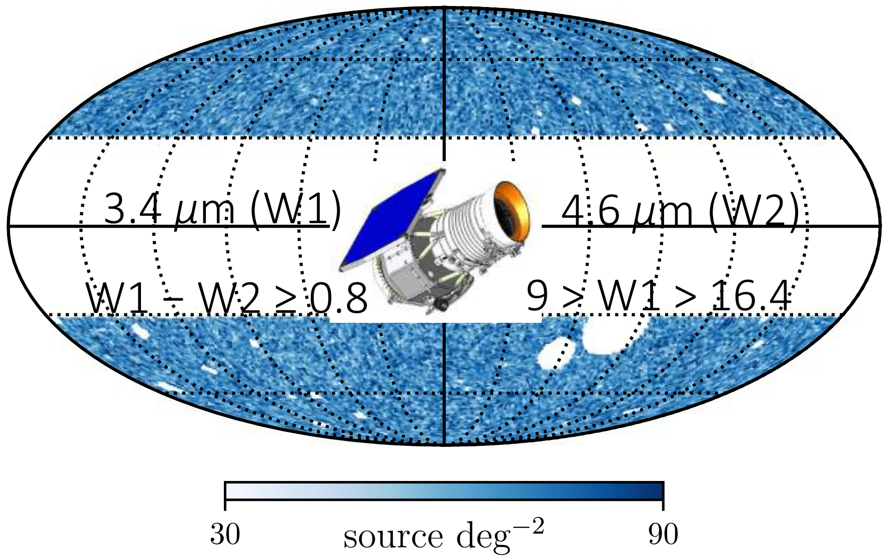


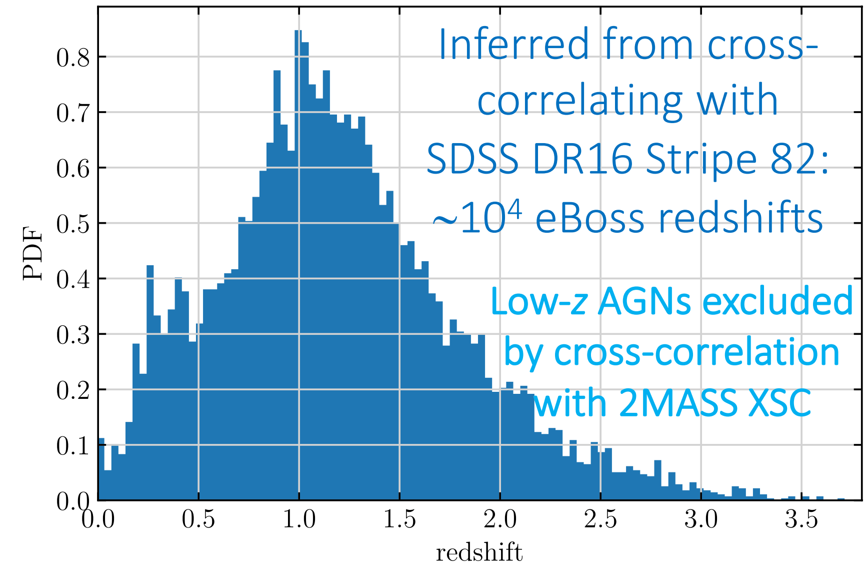
Confirms claim by Singal (ApJ **742**:L23,2011) … however source redshifts are not *directly* measured (also the statistical significance is only 2.8**σ** – by Monte Carlo)

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

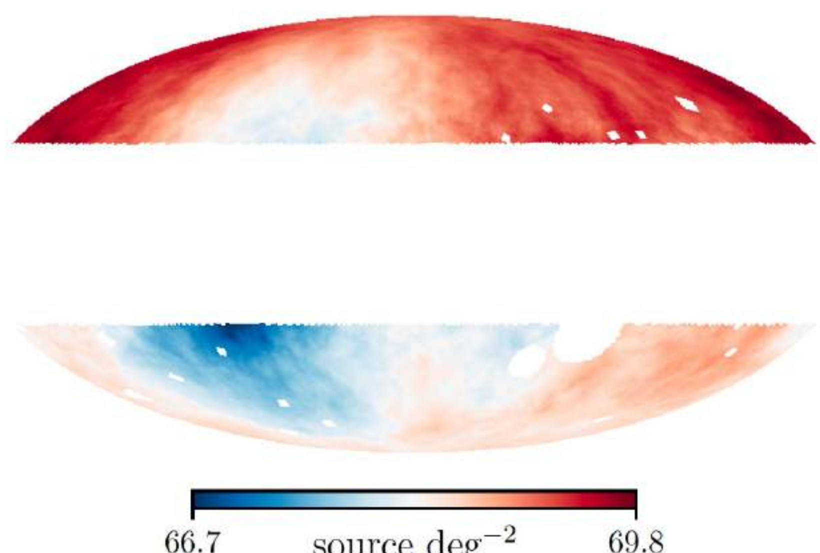
The CatWISE quasar catalogue

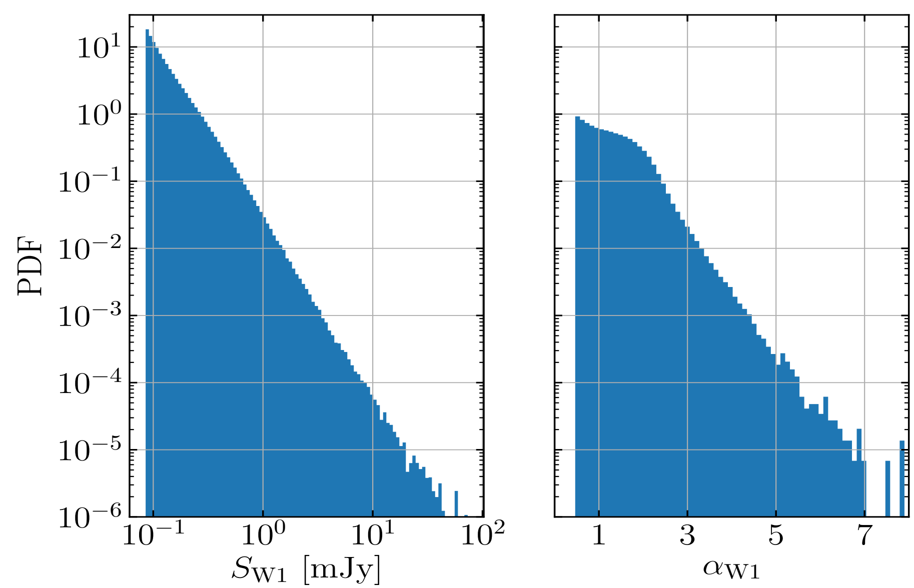
Secrest, Rameez, Von Hausegger, Mohayaee, S.S. & Colin, ApJL **908**:L51,2021





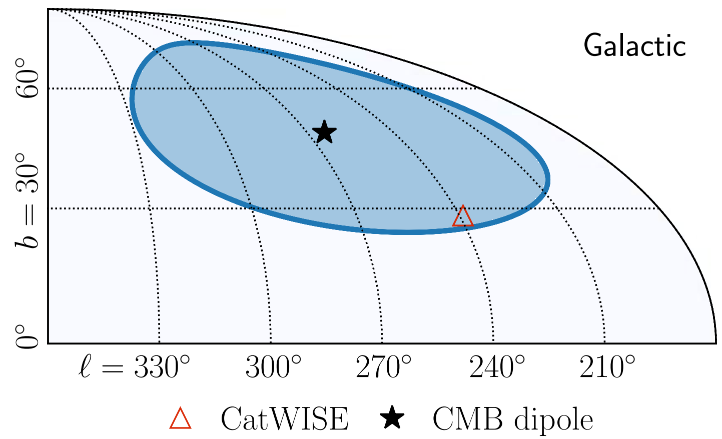
We now have a catalogue of 1.36 million quasars, with 99% at redshift > 0.1



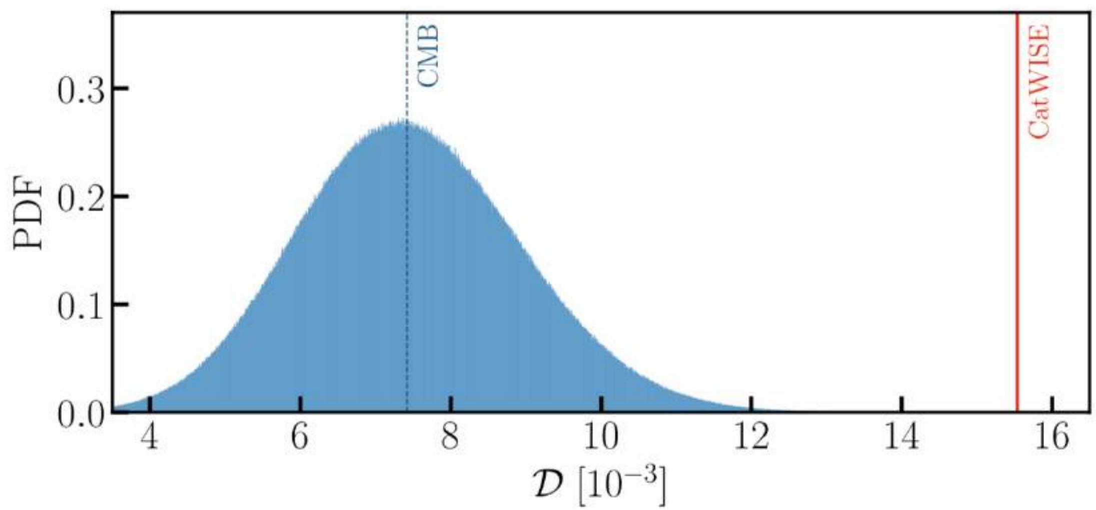


The dipole can be compared to that expected, knowing the spectrum & flux distribution

Our 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



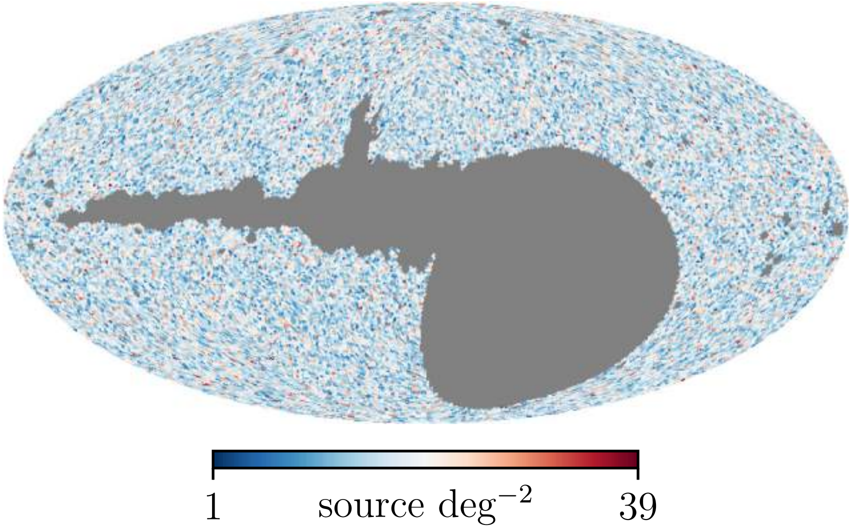
The kinematic interpretation of the CMB dipole is *rejected* with $p = 5 \times 10^{-7} \Rightarrow 4.9\sigma$

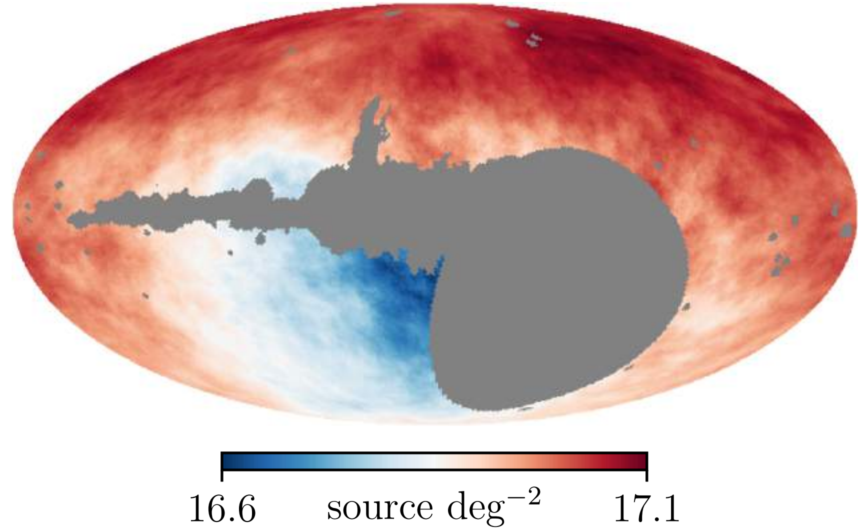
(Data & code available on: https://doi.org/10.5281/zenodo.4431089)

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

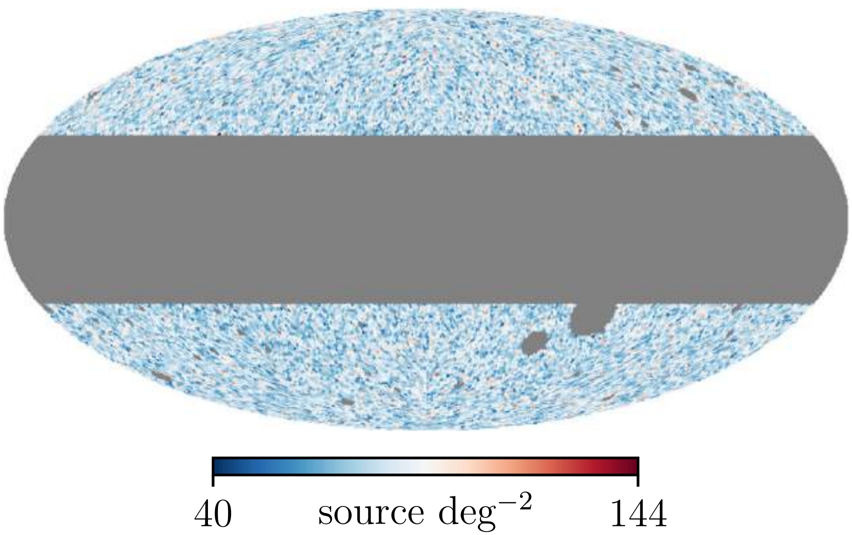
We have further cleaned the NVSS & WISE AGN catalogues of a variety of systematics

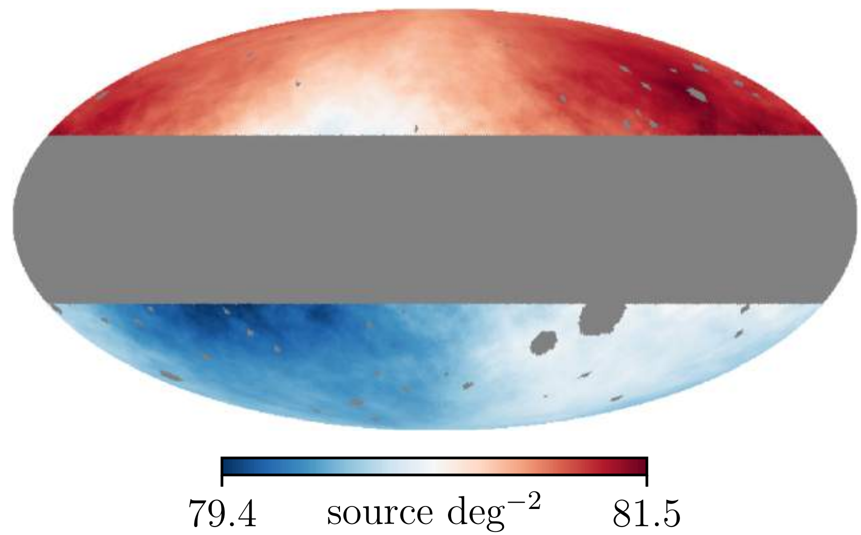
NVSS
508k





WISE
1.6M



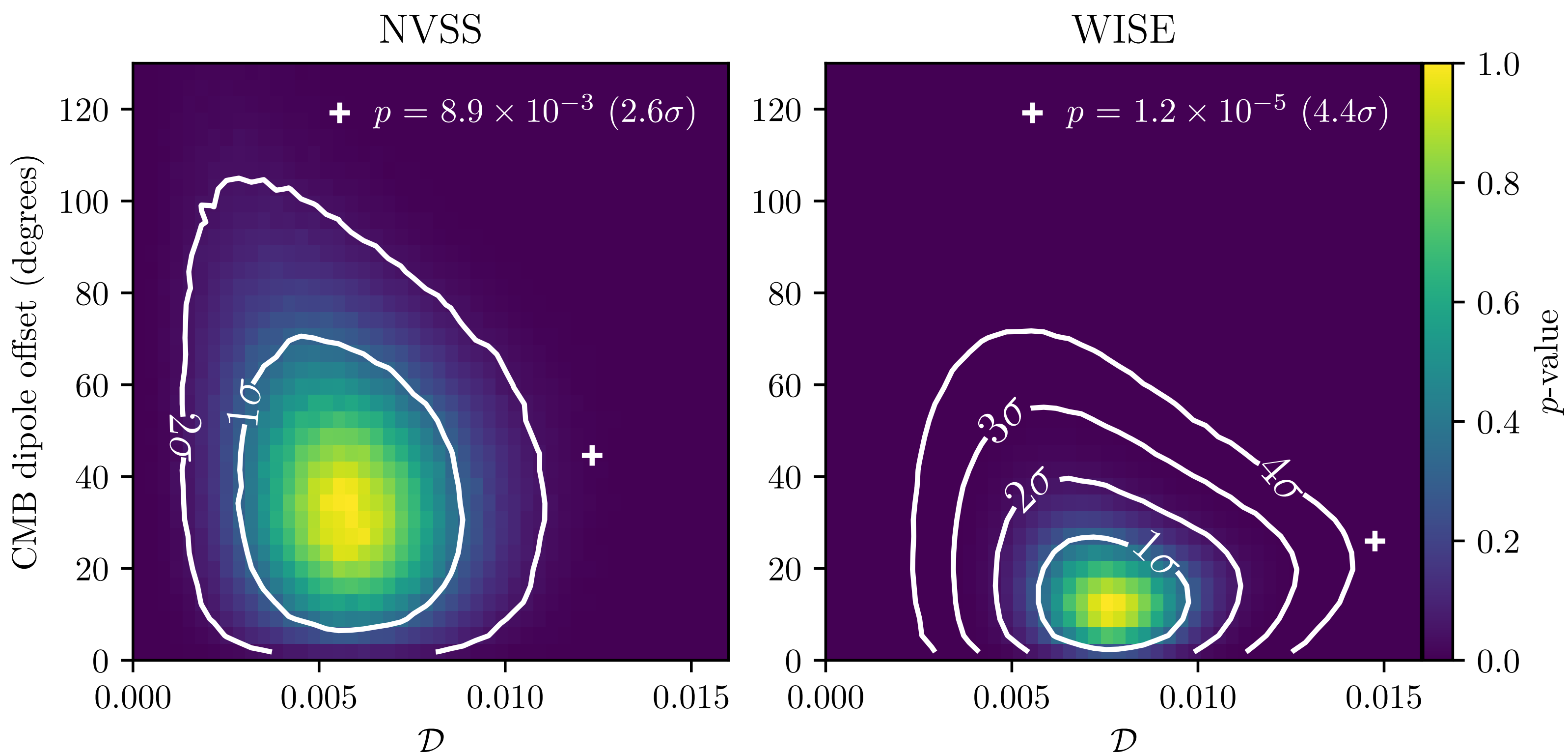


The two dipoles are *consistent* with each other; their vector mean is:

$D = (1.40 \pm 0.13)\times10^{-3}$ 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 5.1**σ**

Secrest, Rameez, Von Hausegger, Mohayaee, S.S., Astrophys. J. Lett. *in press* [arXiv:2206.05624]

Anomalies in Physical Cosmology

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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.)

https://arxiv.org/abs/2208.05018

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 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 'The fitting problem')