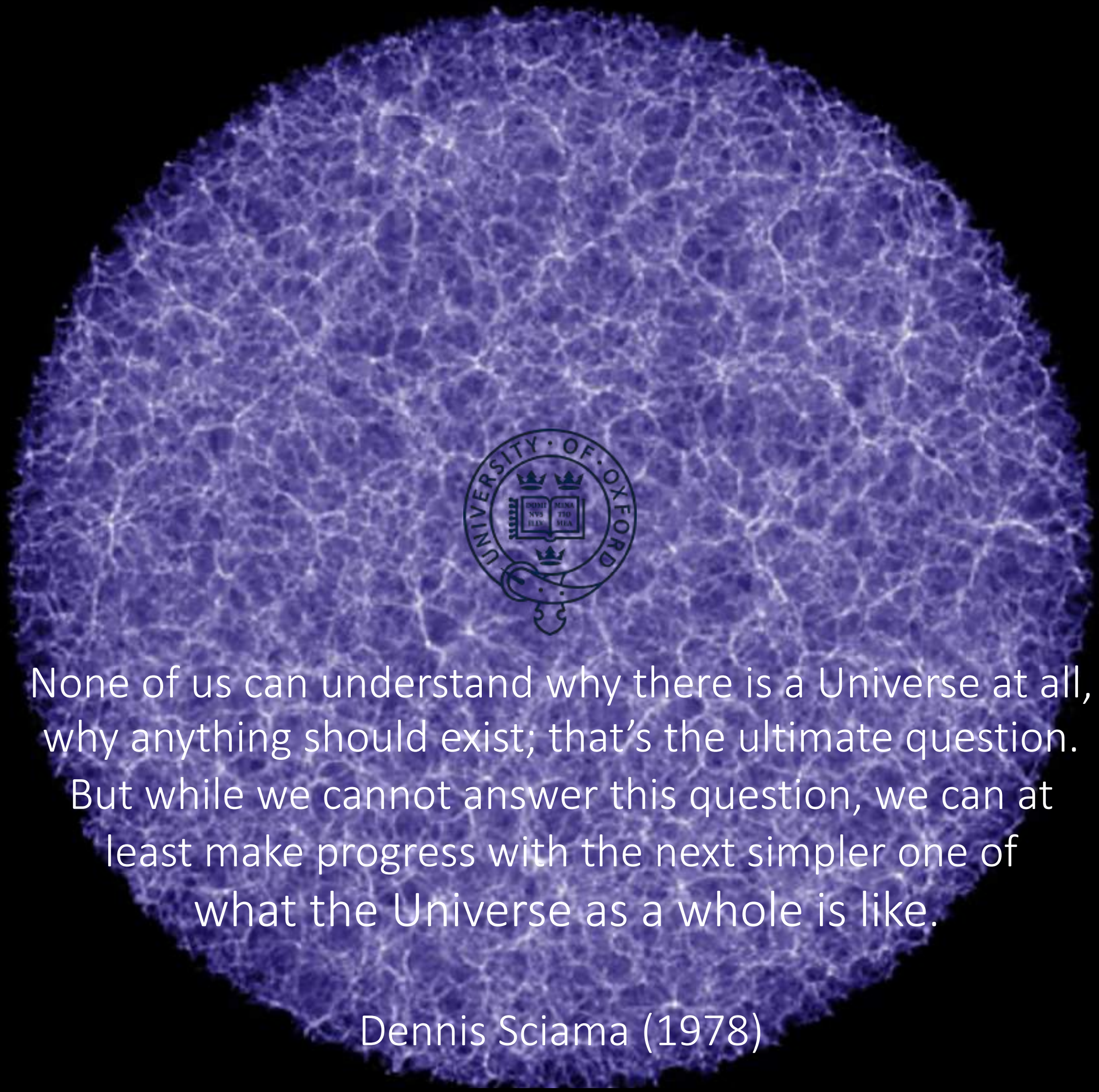
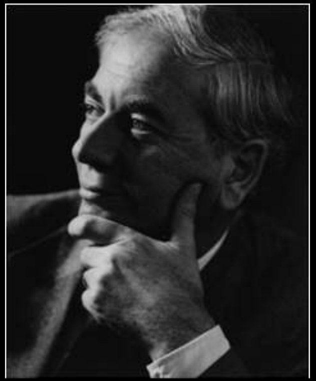
A CHALLENGE TO THE STANDARD COSMOLOGICAL MODEL

Subir Sarkar



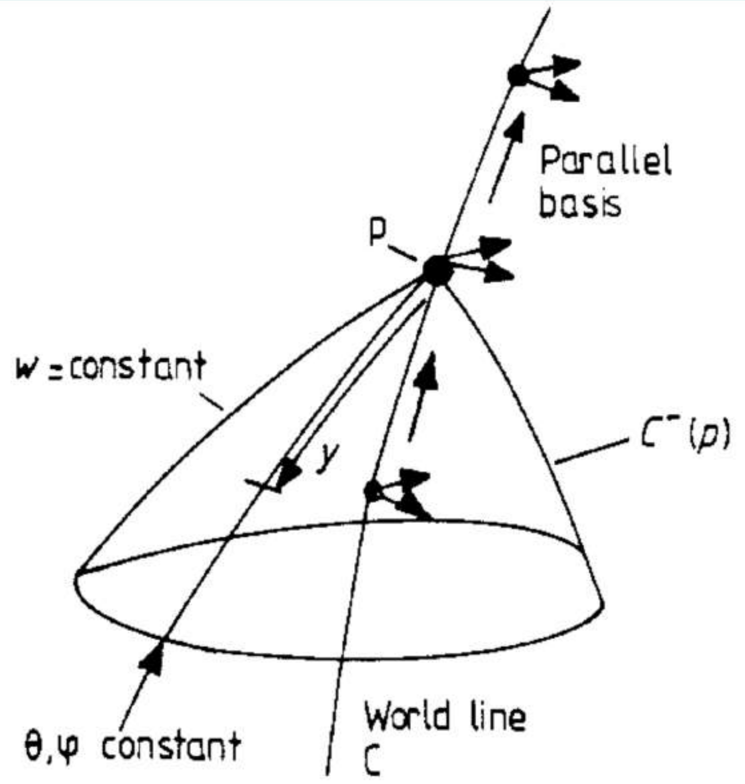
> None of us can understand why there is a Universe at all,
> why anything should exist; that's the ultimate question.
> But while we cannot answer this question, we can at
> least make progress with the next simpler one of
> what the Universe as a whole is like.

Dennis Sciama (1978)



ZURICH PHYSICS COLLOQUIUM, 15 NOVEMBER 2023

ALL WE CAN LEARN ABOUT THE UNIVERSE IS CONTAINED IN 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 *’Kinematics, Dynamics & the Scale of Time’* (1936)

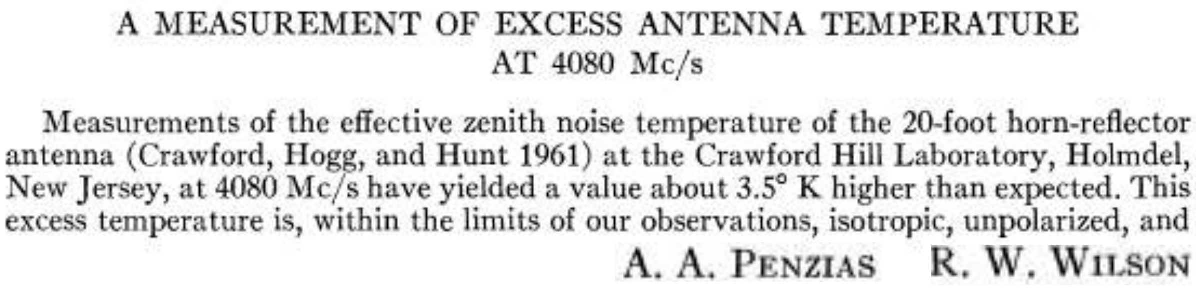
Mathematical Proceedings of the Cambridge Philosophical Society
Volume 51, Issue 4, October 1955 , pp. 678-683

THE COSMOLOGICAL PRINCIPLE
BY D. E. LITTLEWOOD

Many models of the universe have been proposed, by de Sitter, Milne, Bondi and Gold, Hoyle and others. The observed data being insufficient, the models are usually based on some simple hypothesis. The simplest is the cosmological principle, namely, that apart from local irregularities the universe presents the same general aspect at every point. Milne (5) has used a restricted form of the principle, namely, that the aspect is independent of spatial position but is dependent on the observed time from some fixed epoch in the past. Bondi and Gold (1) have proposed the 'perfect cosmological principle' that the aspect is completely independent of space and time.

THE 'PERFECT COSMOLOGICAL PRINCIPLE' WAS ABANDONED FOLLOWING THE DISCOVERY OF THE CMB IN 1964

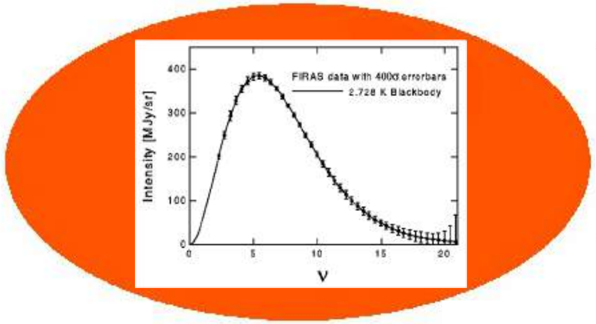
BUT THE NOT-SO-PERFECT COSMOLOGICAL PRINCIPLE LIVED ON ...



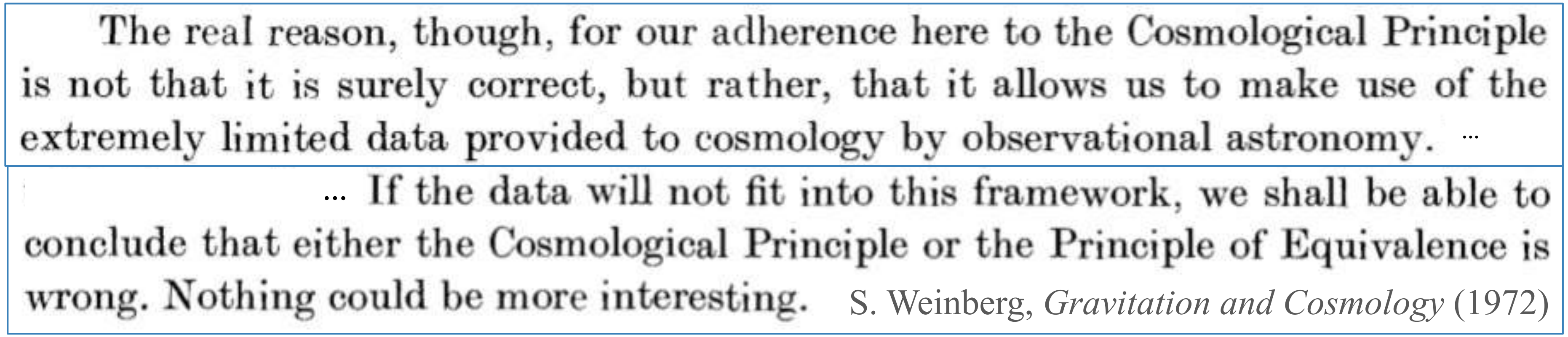
A MEASUREMENT OF EXCESS ANTENNA TEMPERATURE
AT 4080 Mc/s

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

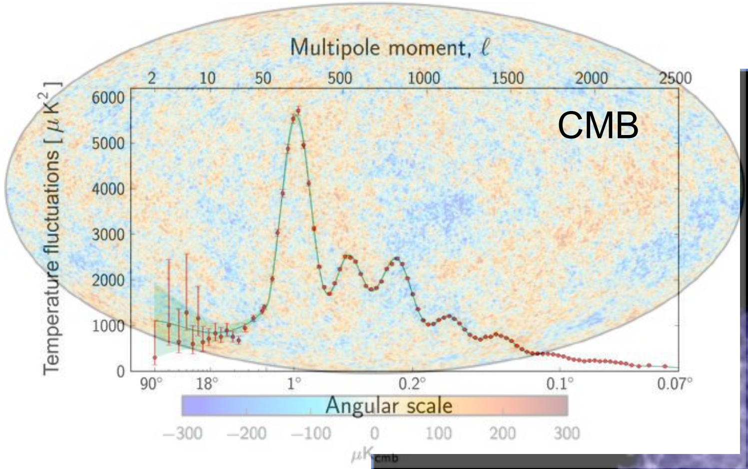
A. A. PENZIAS R. W. WILSON

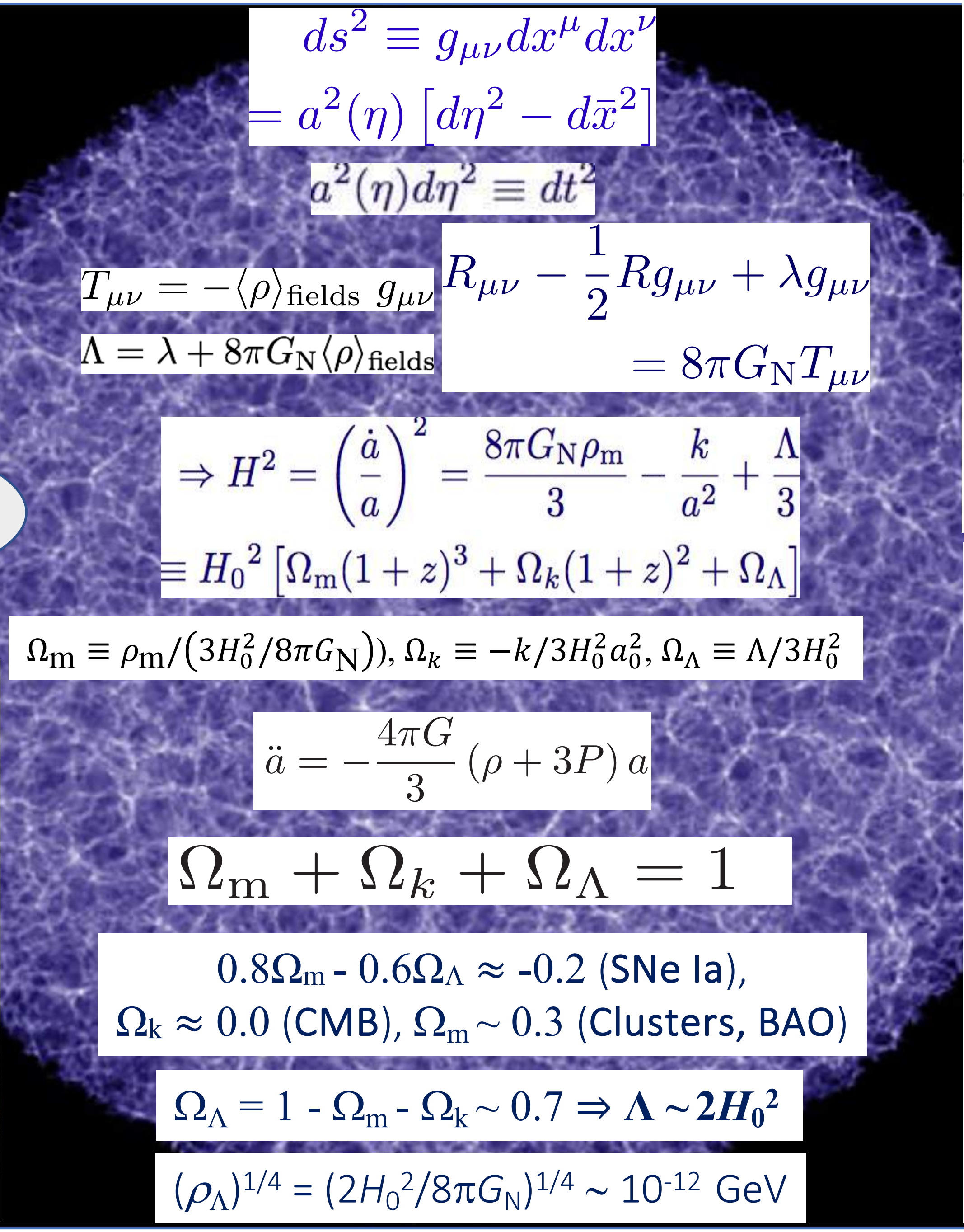



COBE 1992



> 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. S. Weinberg, *Gravitation and Cosmology* (1972)





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

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

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

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

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

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

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

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

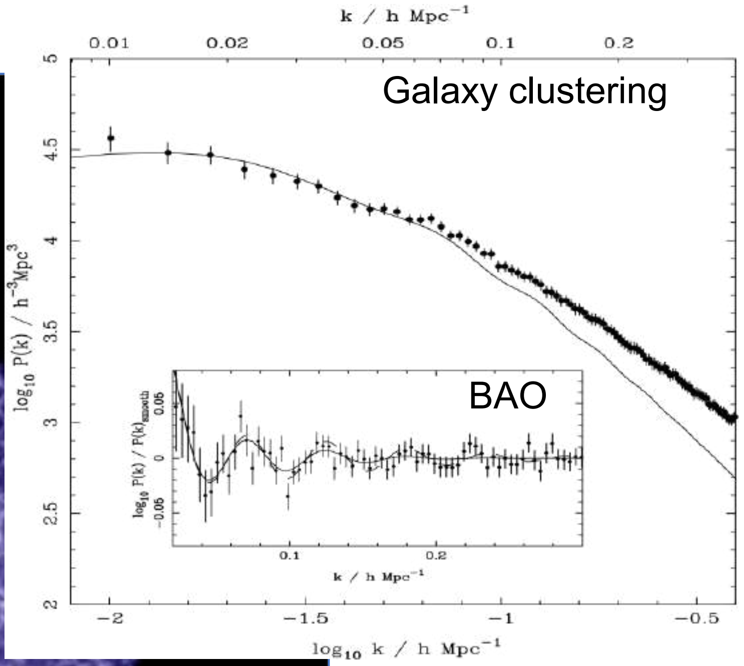
$$\Omega_{\rm m} + \Omega_k + \Omega_\Lambda = 1$$

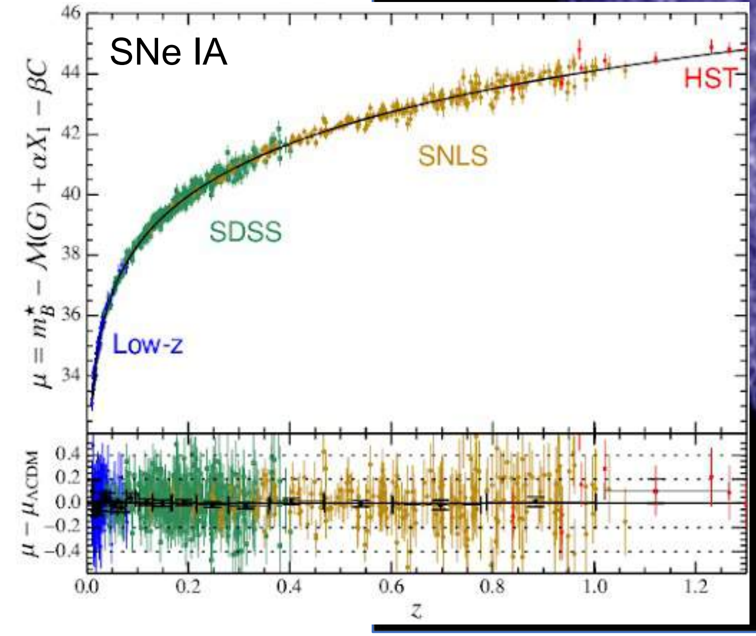
$0.8\Omega_{\rm m}$ - $0.6\Omega_\Lambda \approx$ -0.2 (SNe Ia),
$\Omega_{\rm k} \approx 0.0$ (CMB), $\Omega_{\rm m} \sim 0.3$ (Clusters, BAO)

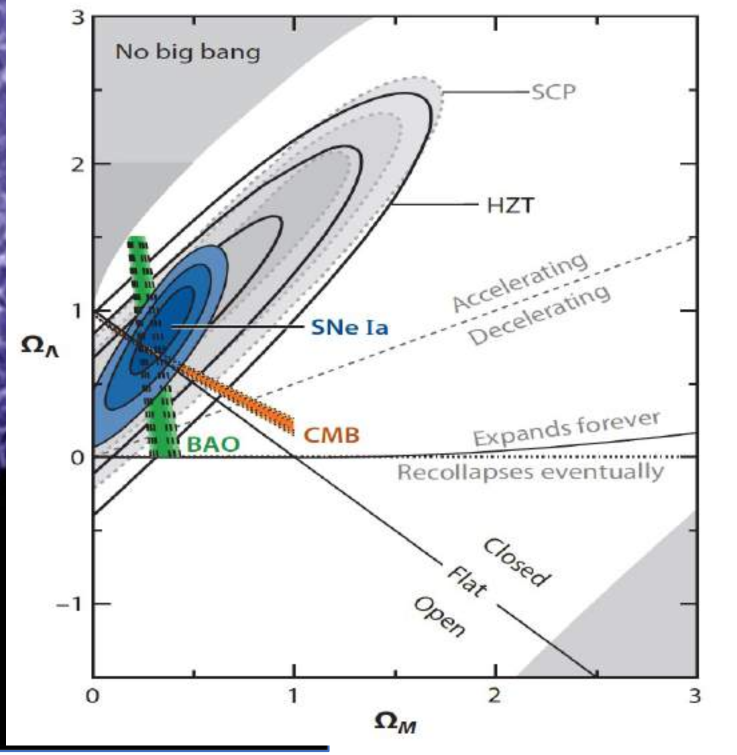
$\Omega_\Lambda = 1 - \Omega_{\rm m} - \Omega_{\rm k} \sim 0.7 \Rightarrow$ **$\Lambda \sim 2H_0^2$**

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

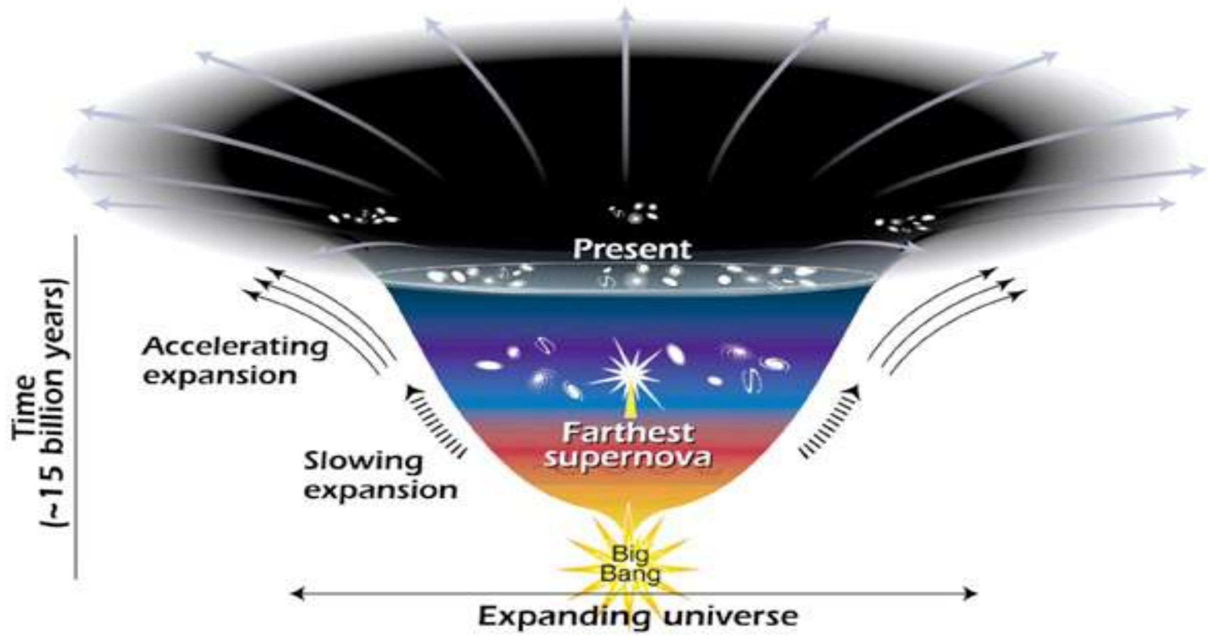
The only scales here are:
$H_0 \sim 10^{-42}$ GeV and
$M_{\rm Pl} \equiv 1/\sqrt{8\pi G_{\rm N}} \sim 10^{19}$ GeV



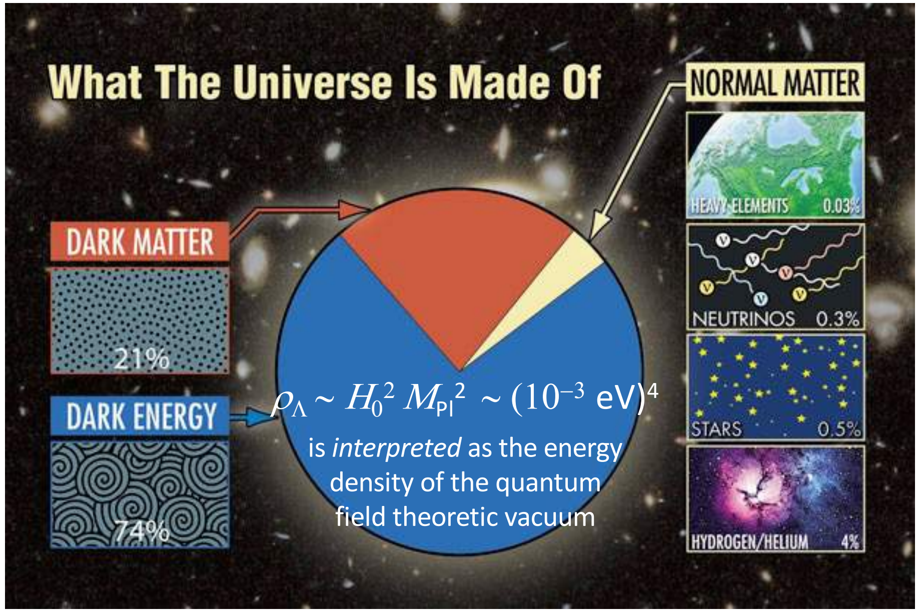




THE COSMOLOGICAL PRINCIPLE IS THE **FOUNDATION** OF THE ‘ΛCDM MODEL’ OF THE UNIVERSE
… DOMINATED BY A COSMOLOGICAL CONSTANT Λ AND UNDERGOING ACCELERATED EXPANSION



It is ‘simple’ if we count Λ as just one parameter, and fits the data (with a few ‘anomalies’) … but lacks a *physical* foundation



$\rho_\Lambda \sim H_0^2 M_{\rm Pl}^2 \sim (10^{-3}\,\text{eV})^4$

is *interpreted* as the energy density of the quantum field theoretic vacuum

There has been substantial investment in major satellites and telescopes to *measure the parameters* of this ‘standard 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

$$-\mu^2\phi^\dagger\phi + \frac{\lambda}{4}(\phi^\dagger\phi)^2, m_H^2 = \lambda v^2/2$$

$$\mathcal{L}_{\mathrm{eff}} = F^2 + \bar{\Psi}\,\not{D}\Psi + \bar{\Psi}\Psi\Phi + (D\Phi)^2 + V(\Phi)$$

renormalisable

$$+\frac{\bar{\Psi}\Psi\Phi\Phi}{M} + \frac{\bar{\Psi}\Psi\bar{\Psi}\Psi}{M^2} + \ldots$$

neutrino mass

proton decay

non-renormalisable

However the ‘super-renormalisable’ operators become more important as *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 (strictly speaking *not* calculable) is:

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

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

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

Interpreting Λ as vacuum energy raises the 'coincidence problem':

Why is $\mathbf{\Omega_\Lambda \approx \Omega_m}$ *today*?

An evolving ultralight scalar field ('quintessence') displays '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 Hubble radius scale $1/H_0$ so as to mimic vacuum energy … this scale is *absent* in a fundamental theory and must be put in by hand

(This is the case with *every* proposal to "explain" dark energy: massive gravity, chameleon fields, …)

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

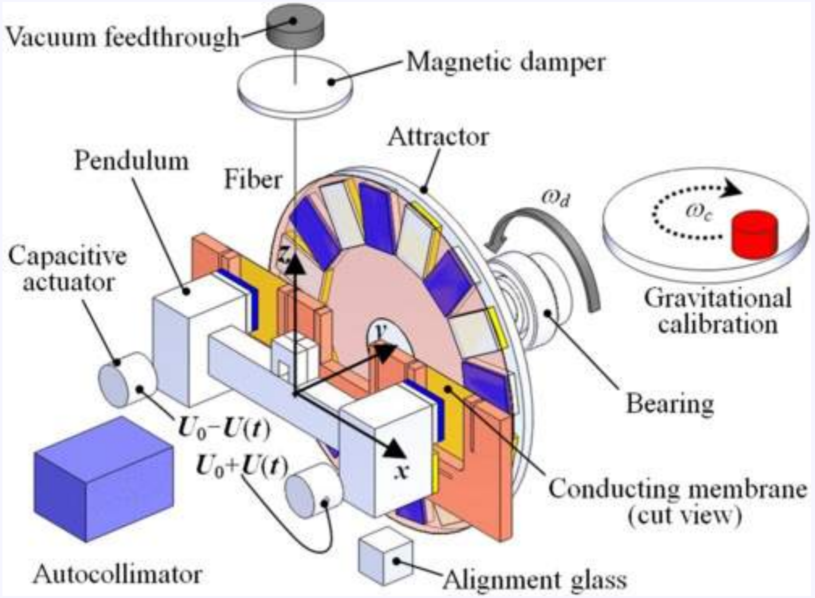
Therefore *every* attempt to explain the coincidence problem is severely fine-tuned

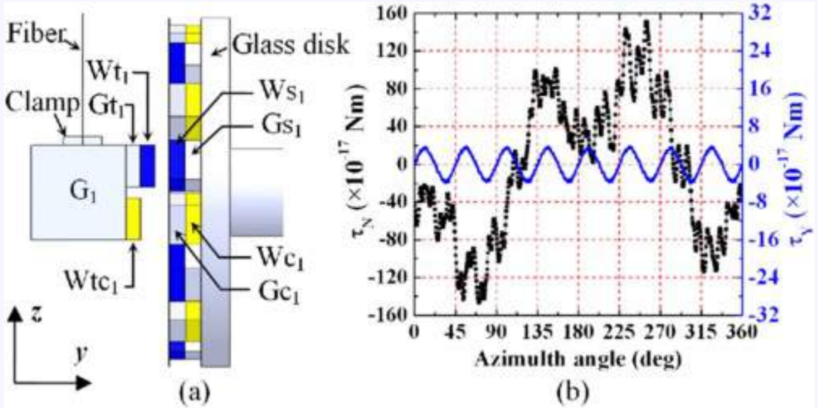
Suggestion that *S*-matrix formulation of quantum gravity *excludes* de Sitter vacua
(Dvali, *Symmetry* **21**:3,2021; Obied, Ooguri, Spodyneiko & Vafa, 1806.08362)

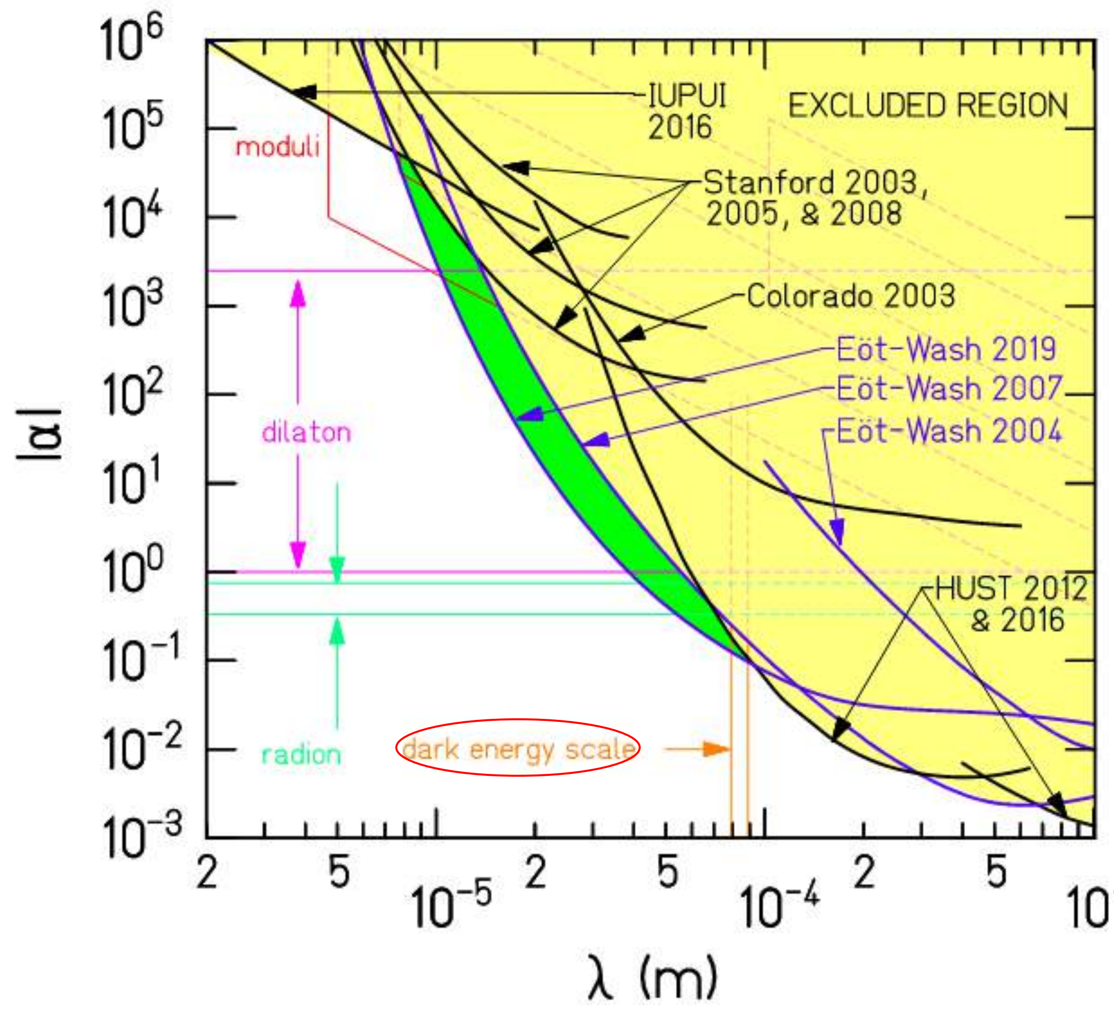
Do we infer $\Lambda \sim H_0^2$ from observations simply because H_0 ($\sim 10^{-42}$ GeV) is the *only* scale in the F-R-L-W model and enters in the interpretation of every cosmological observation … so its value is imprinted on Λ by *construction*?

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**

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



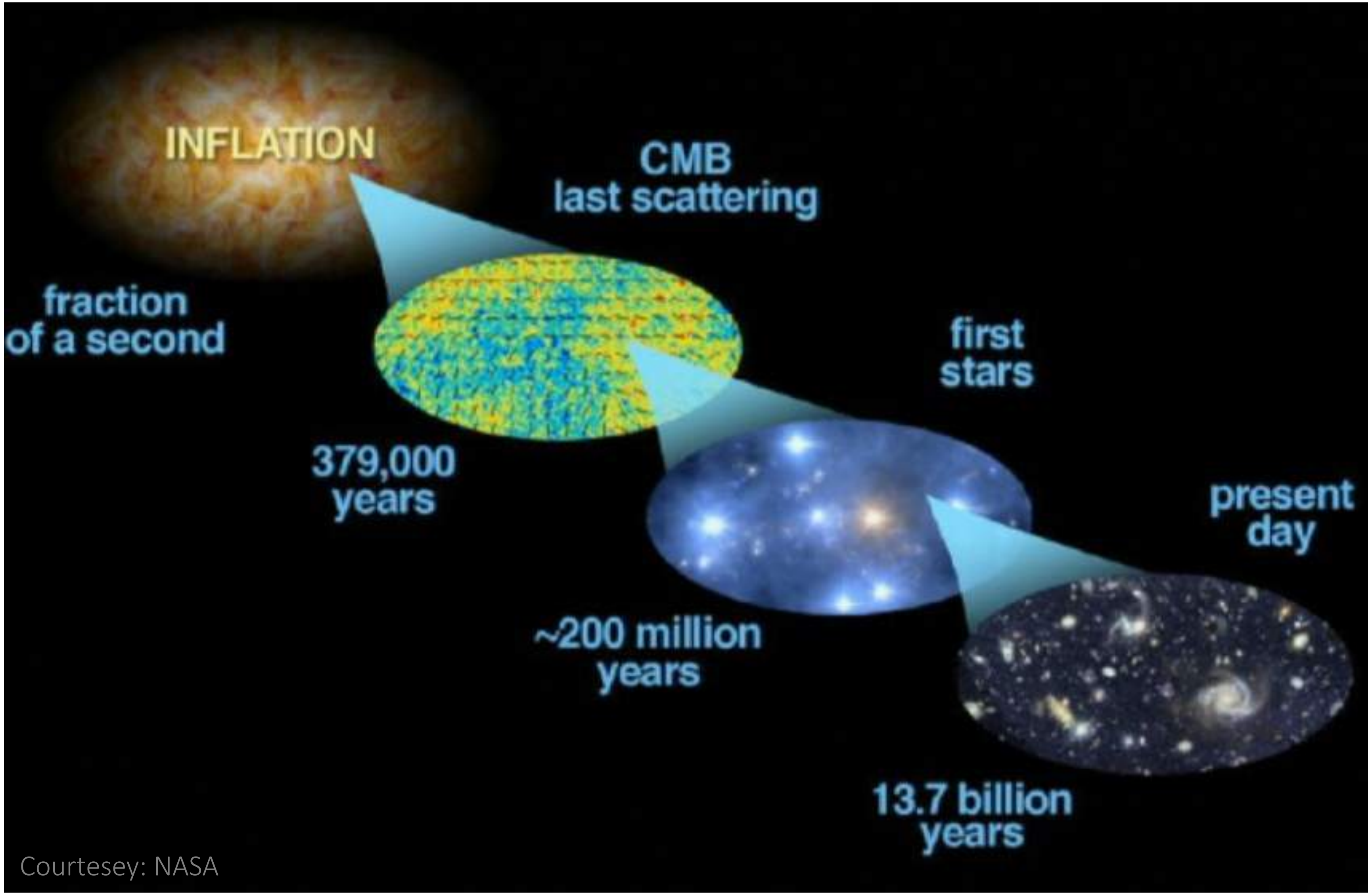




Lee *et al*, PRL **124**:101101,2020

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

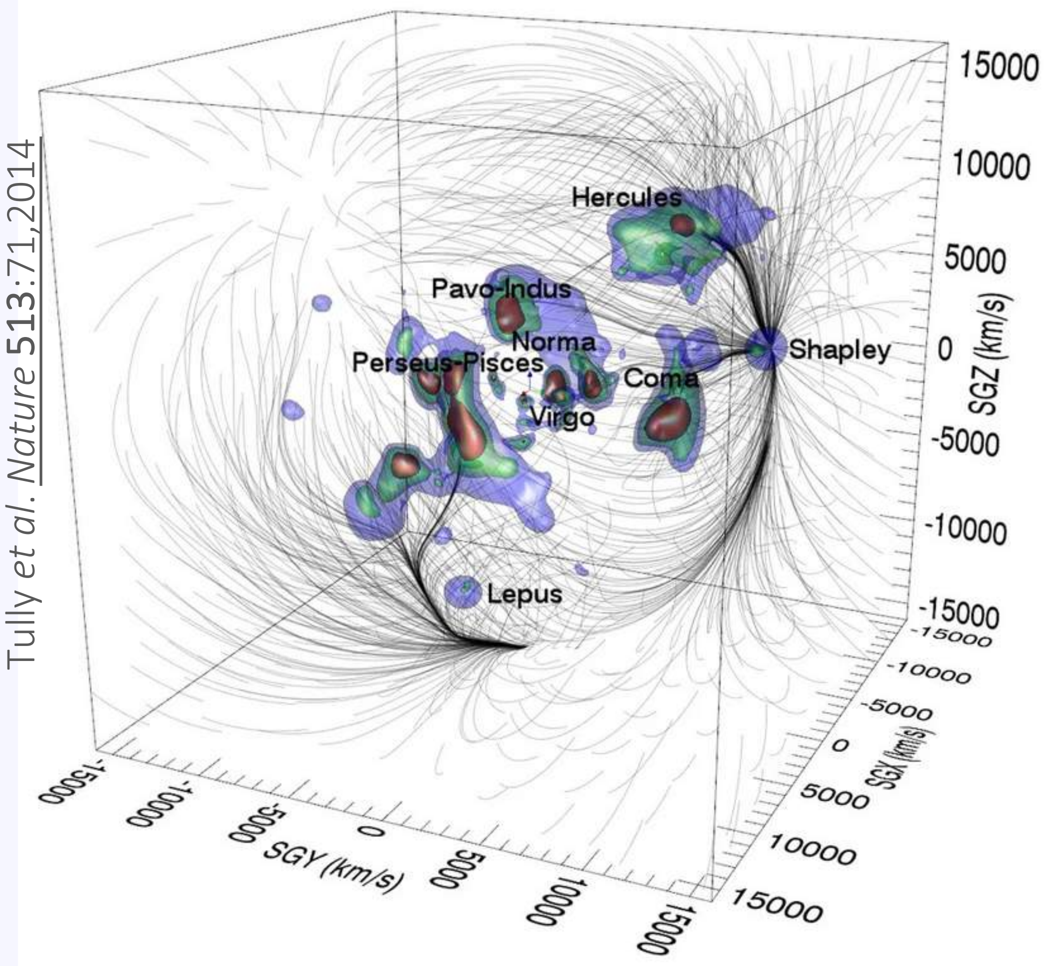
ΛCDM + STANDARD MODEL OF STRUCTURE FORMATION



Courtesey: NASA

The ~10^{-5} CMB temperature fluctuations are due to **~gaussian scalar density perturbations with ~scale-invariant spectrum**, generated during an early **~de Sitter phase of inflationary expansion** … these perturbations have grown into the **large-scale structure** of galaxies we see today through gravitational instability in a sea of (cold) **dark matter**

THE REAL UNIVERSE IS *INHOMOGENEOUS* ... HOW WELL DOES IT CONFORM TO THE F-L-R-W MODEL DESCRIPTION?



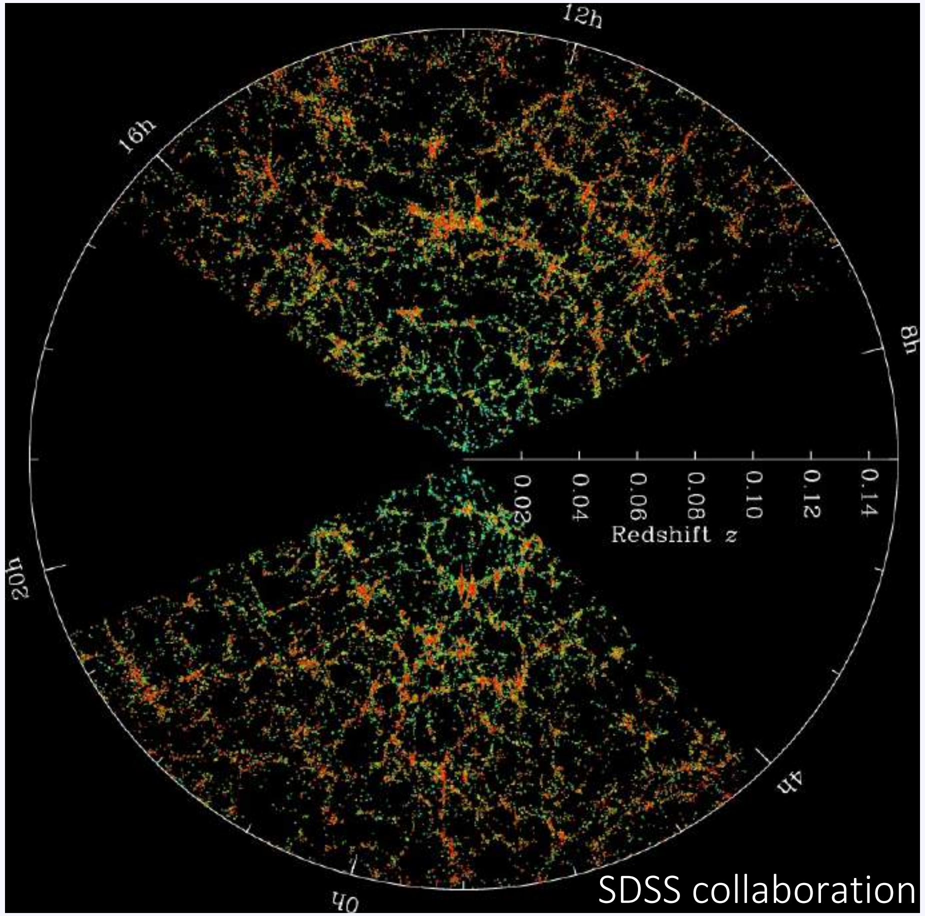
Tully *et al.* Nature 513:71,2014

Peculiar velocity: $u = cz - H_0 d$

Is it justified to approximate it as *exactly* homogeneous?
… to assume that we are '*typical*' observers?
… to assume that all observed directions are *equivalent*?

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

… and on the largest scales (~ 600 Mpc) mapped so far →



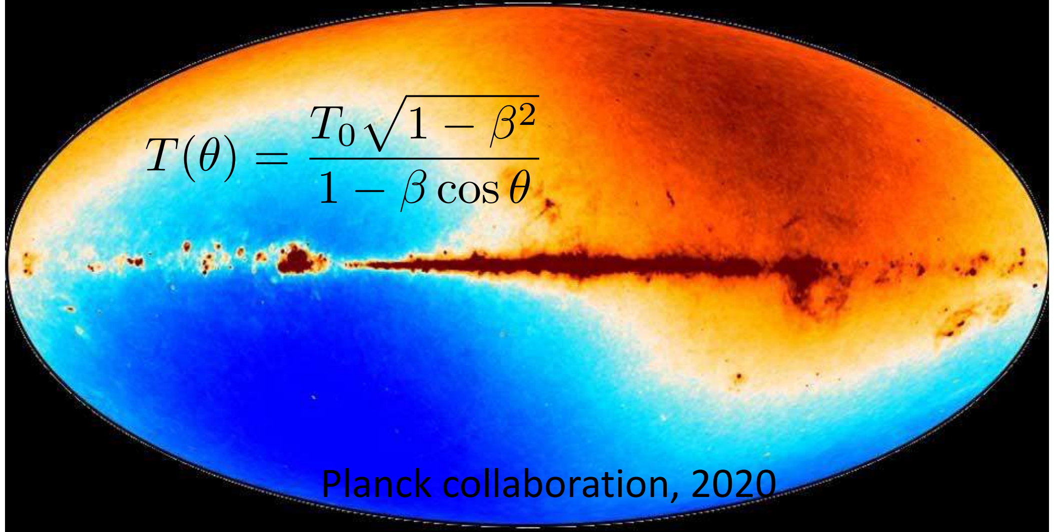
SDSS collaboration

We are flowing towards the Shapley supercluster – supposedly pulled by the 'Great Attractor' – our 'peculiar velocity' should then fall off as ~1/r as we converge to the CMB frame in which the universe is supposed to be isotropic & homogeneous .. so can be described by the F-L-R-W metric

THE UNIVERSE IS *NOT* ISOTROPIC AROUND US

Stewart & Sciama *Nature* **216**:748,1967

The CMB has a dipole anisotropy with $\Delta T/T \sim 10^{-3}$



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

Planck collaboration, 2020

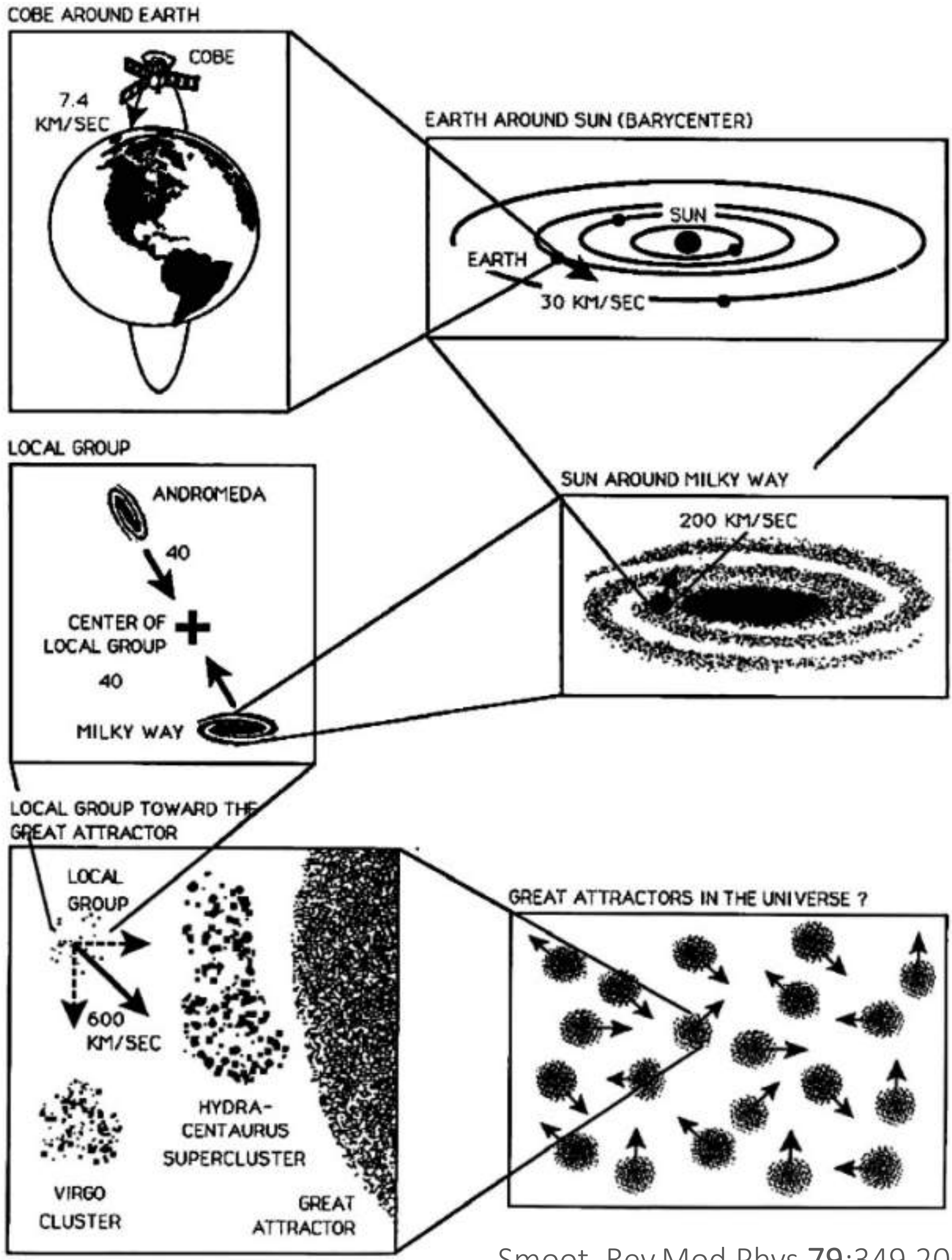
This was predicted based on our ‘peculiar’ velocity

Peebles & Wilkinson, *PRL* **174**:2168,1968

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°

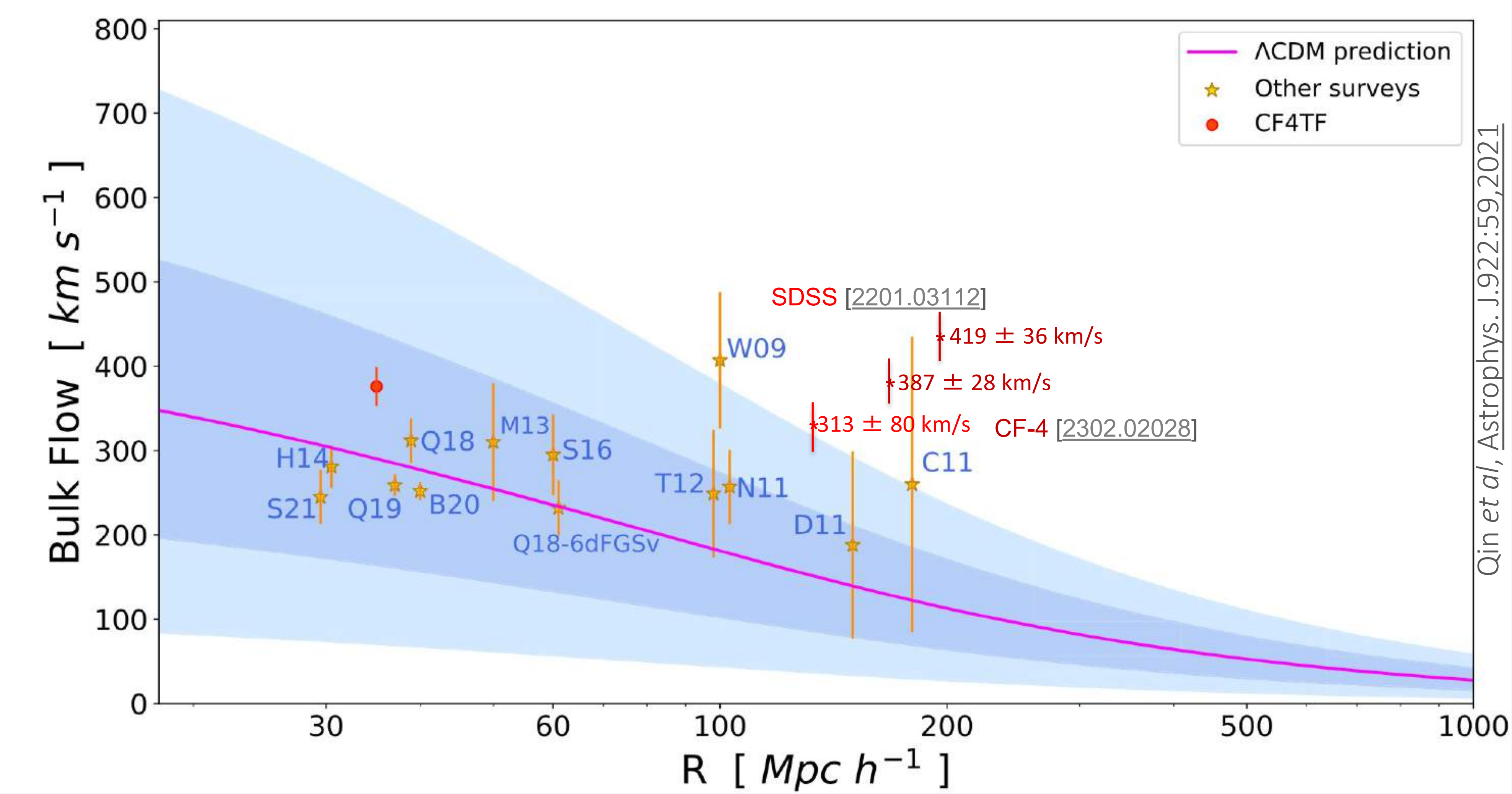
This motion is presumed to be due to *local* inhomogeneity in the matter distribution … according to the theory of structure formation in ΛCDM we should converge to the ‘CMB frame’ by averaging on scales larger than $\sim 100/h$ Mpc

So all observational data is routinely ‘corrected’ by first transforming to the CMB frame in which FLRW *should* hold



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

BUT CONVERGENCE TO THE ‘CMB FRAME’ IS *NOT* SEEN OUT TO $\gtrsim 200h^{-1}$ MPC



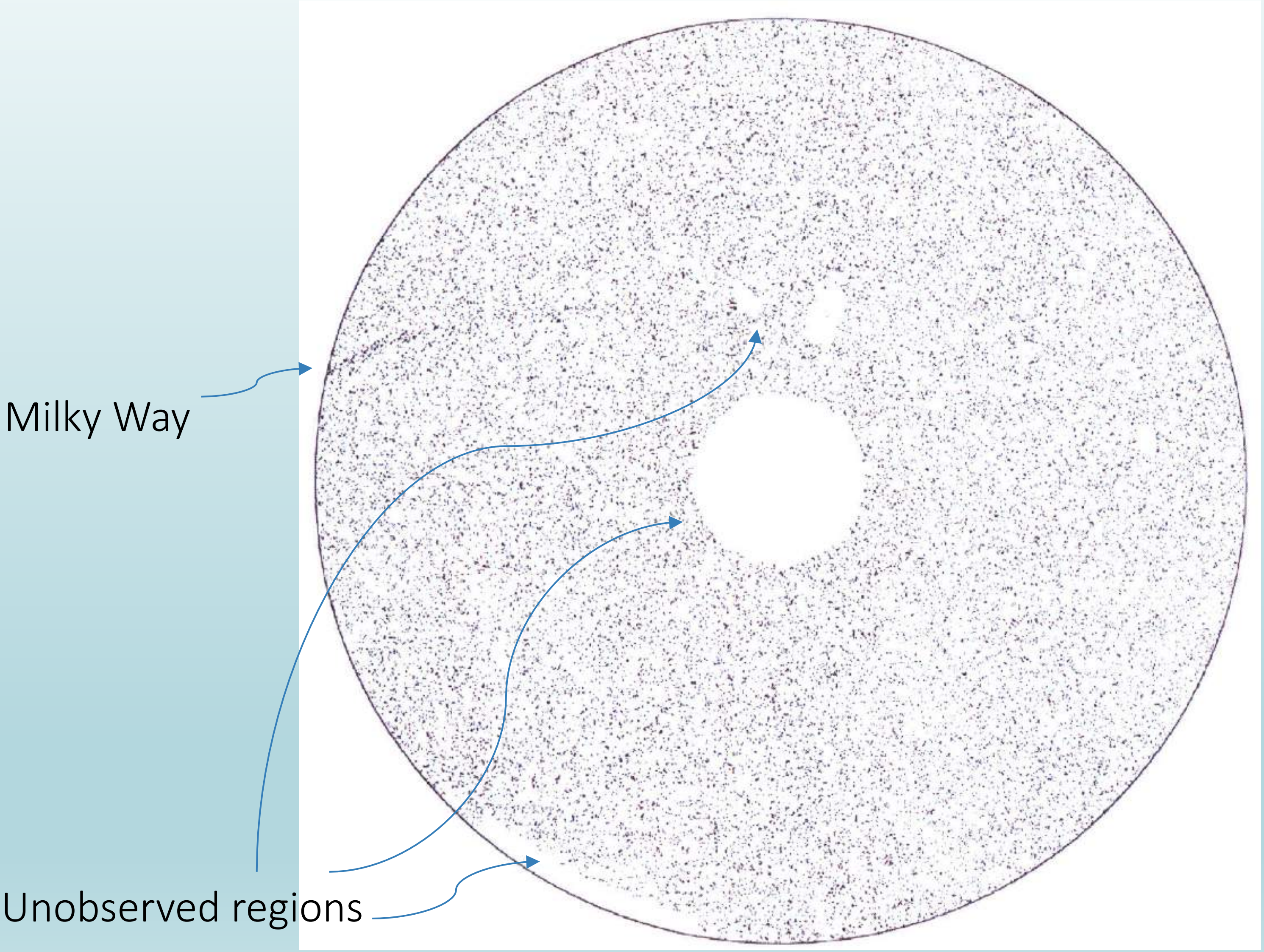
Qin *et al*, Astrophys. J.922:59,2021

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.

“This bulk flow is in even greater tension with the standard model, having ~1.5×10^{-4} % probability of occurring”

Analysing the large-scale bulk flow using cosmicflows4, Watkins *et al*, MNRAS **524:**1885,2023

TEXTBOOKS SAY THAT THE DISTRIBUTION OF DISTANT RADIO SOURCES DEMONSTRATES THE ISOTROPY OF THE UNIVERSE



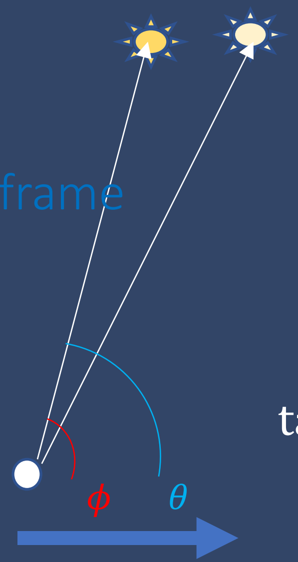
Peebles, *Principles of Physical Cosmology*, 1993

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

IF THE CMB DIPOLE IS DUE TO OUR MOTION WRT THE FRAME IN WHICH THE UNIVERSE IS ISOTROPIC THEN WE SHOULD SEE A SIMILAR DIPOLE IN THE SKY MAP OF COSMOLOGICALLY DISTANT SOURCES

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

Aberration (Bradley 1728)



Rest frame

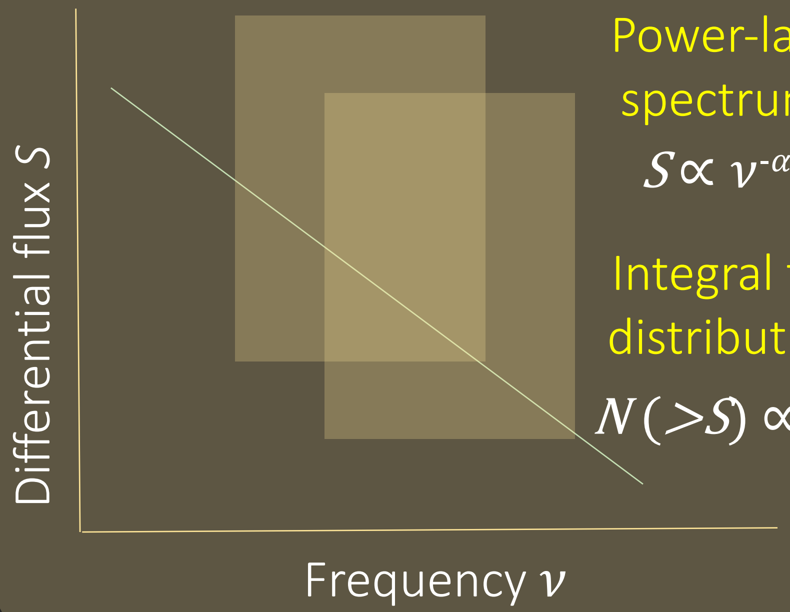
Moving frame

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

Observer, velocity $\boldsymbol{v}$

+

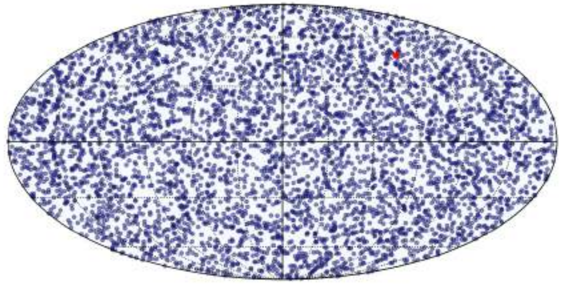
Doppler boosting (Doppler 1842)



Power-law spectrum $S \propto \nu^{-\alpha}$

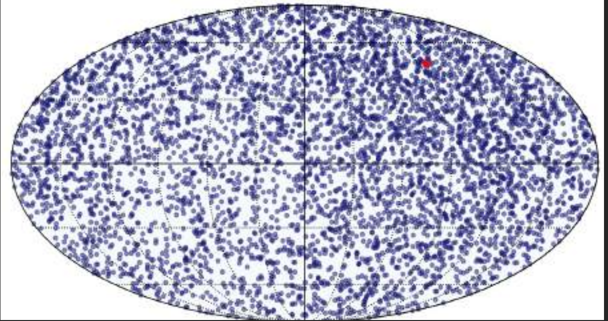
Integral flux distribution: $N(>S) \propto S^{-x}$

Galaxies / quasars in CMB “rest frame”



Aberration ⇒ Source positions compressed in direction of motion

Doppler boosting ⇒ Otherwise too-faint objects boosted above the catalogue flux limit

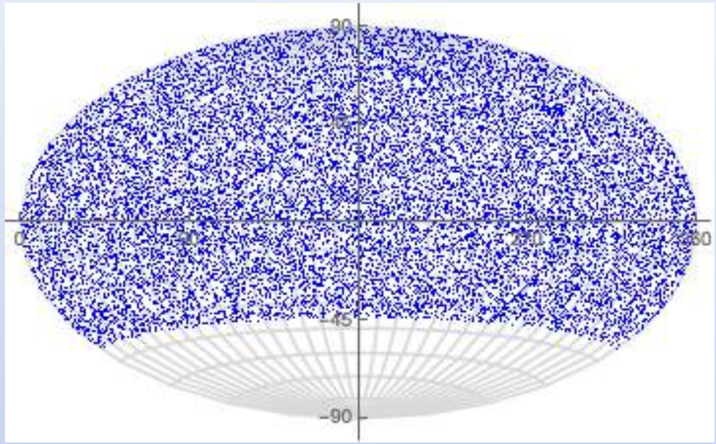


Flux-limited catalogue ➞ *more* sources in direction of motion

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

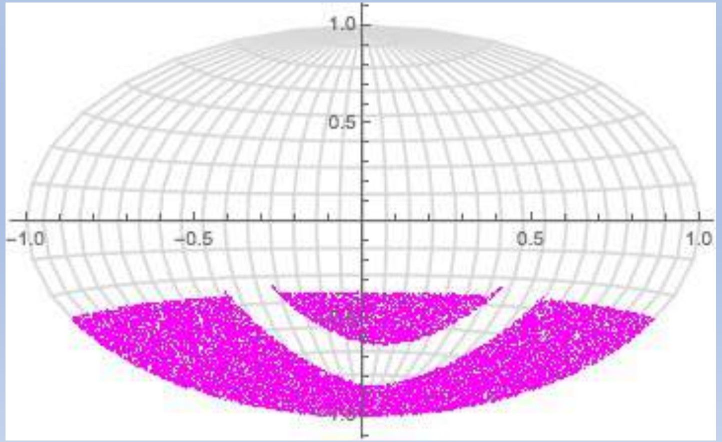
THE NRAO VLA SKY SURVEY (NVSS)

1.4 GHz survey down to Dec = -40.4º
1,773,488 sources >2.5 mJy



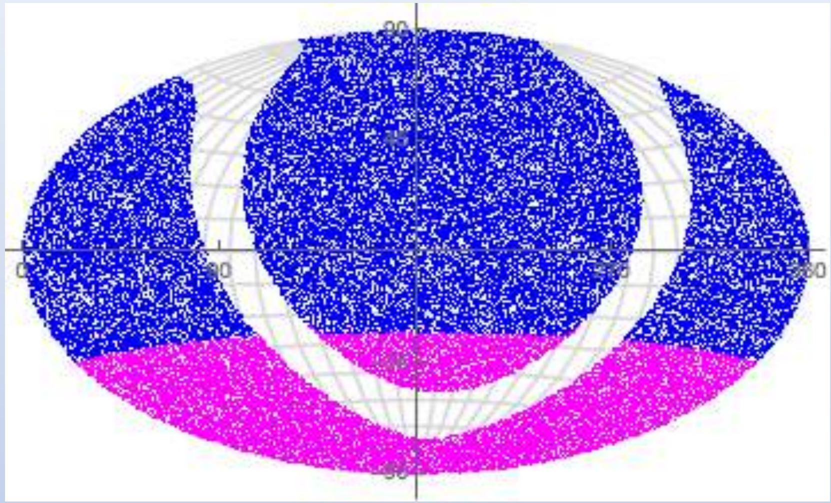
SYDNEY UNIVERSITY MOLONGLO SKY SURVEY (SUMSS)

843 MHz survey below Dec = -30º
211,050 sources (with similar sensitivity & resolution as NVSS)



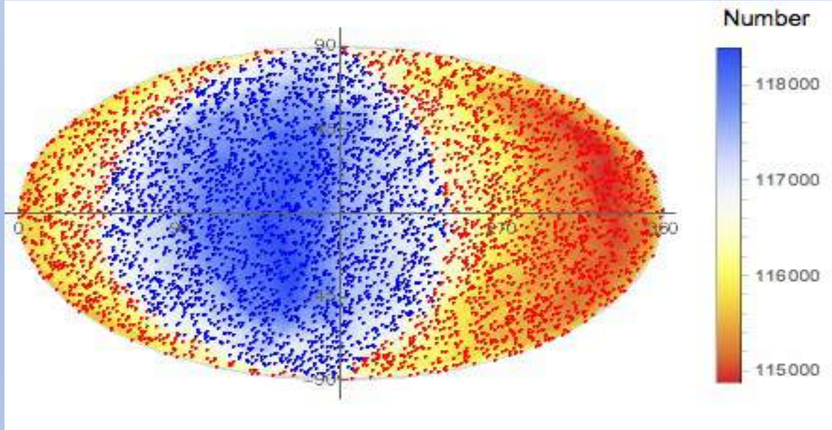
THE NVSUMSS ALL SKY CATALOGUE

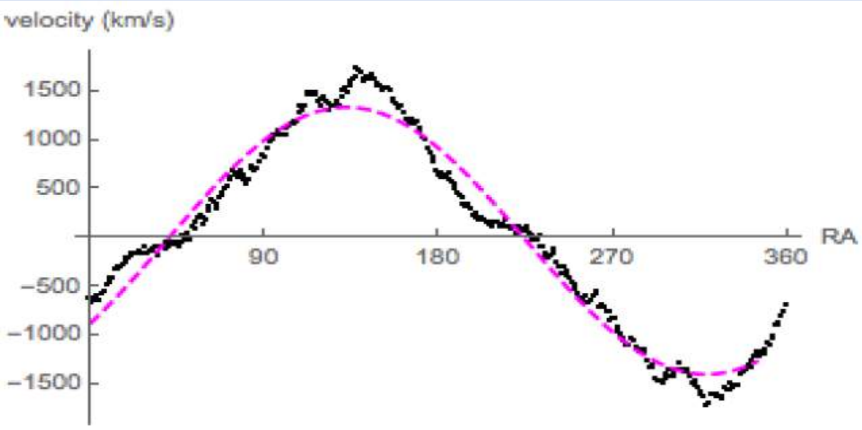
[Rescale the SUMSS fluxes by (843 MHz/1.4 GHz)$^{-0.75}$ = 1.46 to match with NVSS]



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

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



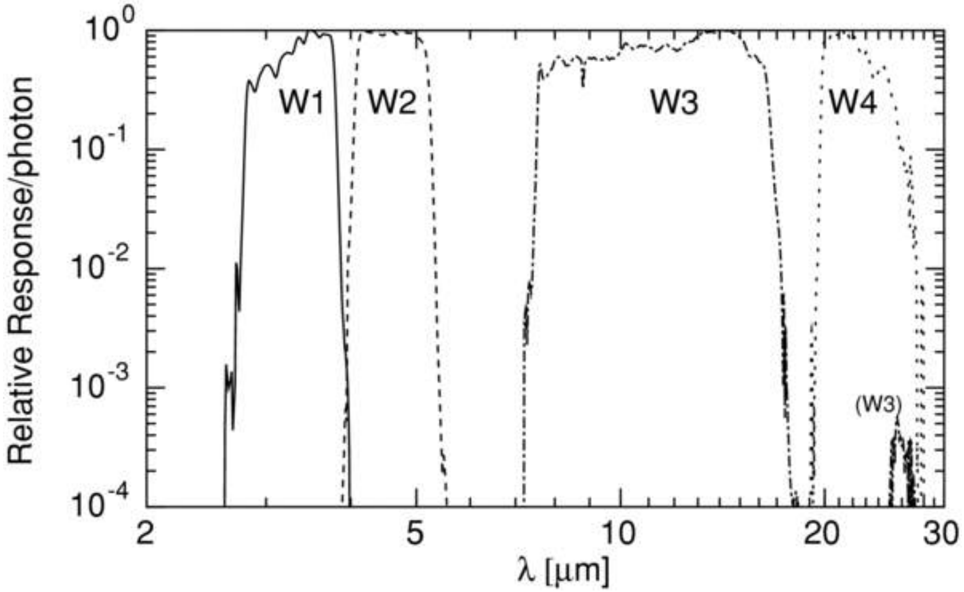


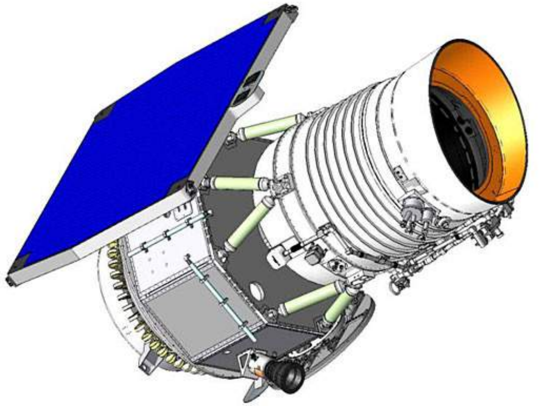
Confirms claim by Singal (ApJ **742**:L23,2011) … however the statistical significance of the anomaly is only 2.8**σ** (moreover source redshifts are *not* directly measured)

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

THE CATWISE QUASAR CATALOGUE

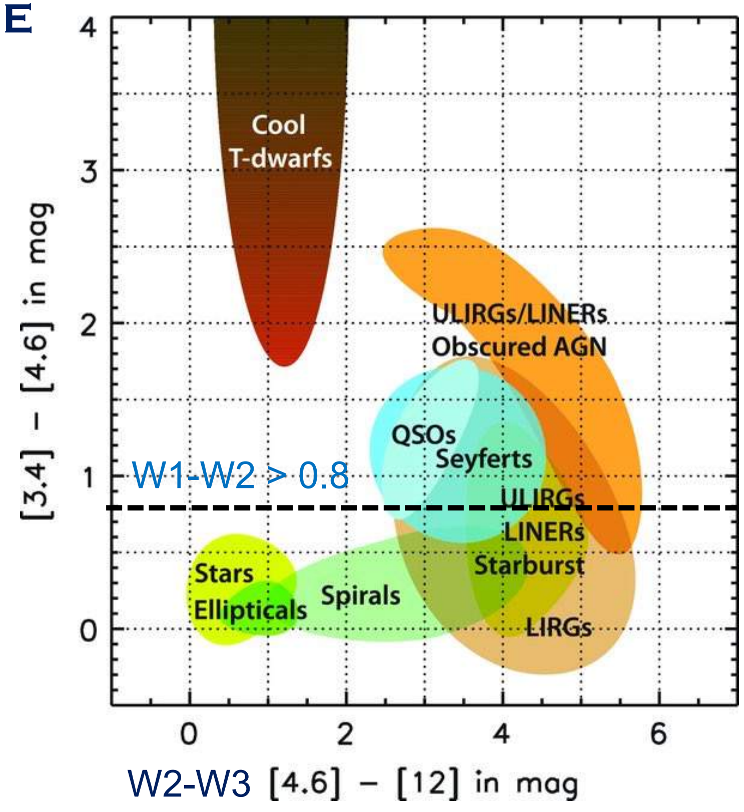
Our colour cuts selectively select quasars … sample purity is 99% (confirmed by eBOSS spectra of sub-sample)



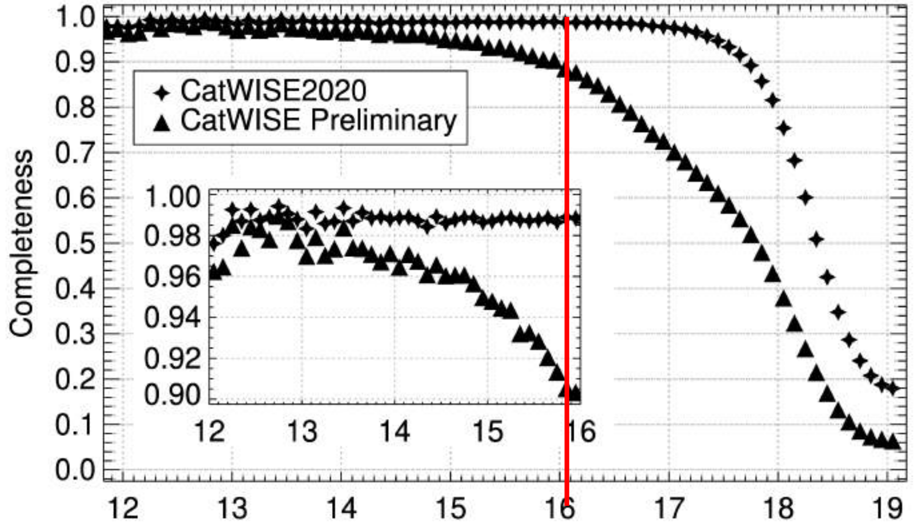


All-sky infrared survey in 4 bands: 3.4, 4.6, 12, 22 μm

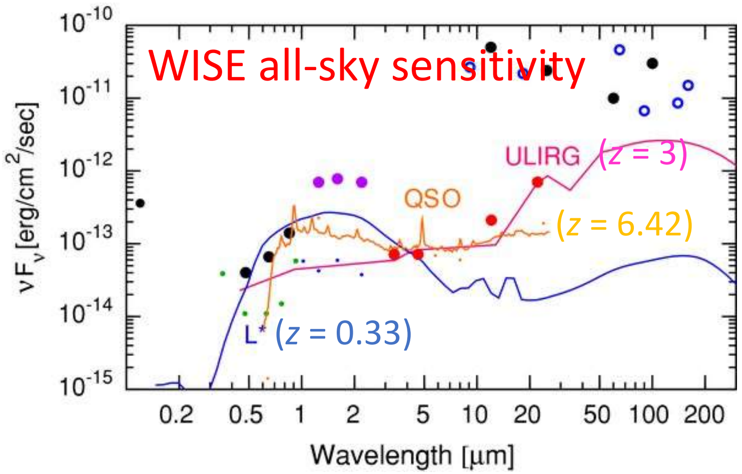
Directionally unbiased survey
arcsecond angular resolution
multi-band photometry

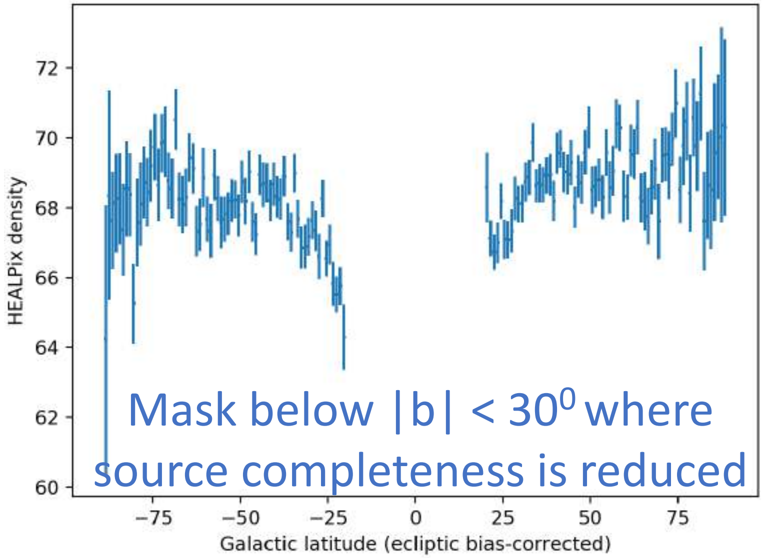


Wright *et al.*, *AJ* **140**:1868,2010



Magnitude cut W1 < 16.4 ensures completeness

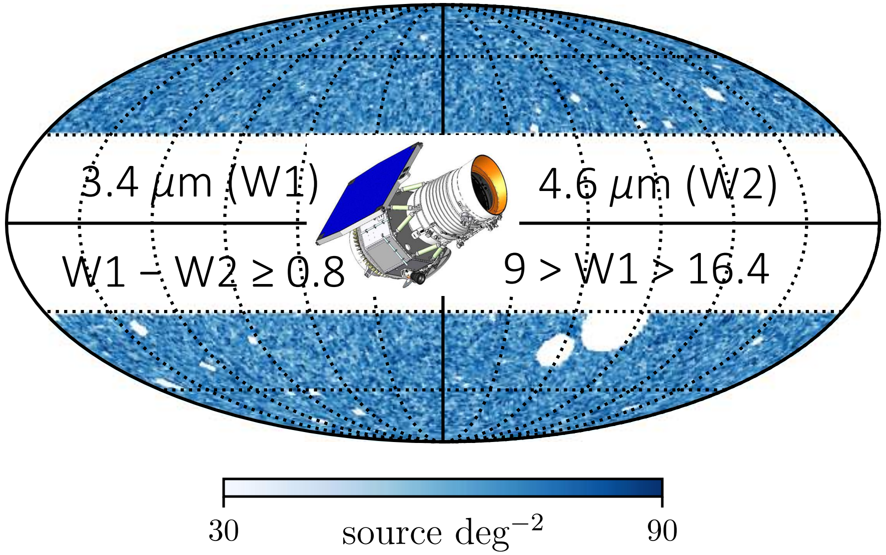




Mask below |b| < 30^0 where source completeness is reduced

The CatWISE quasar catalogue

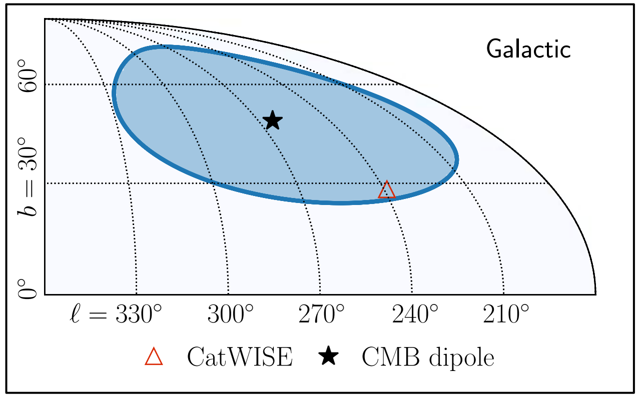
Secrest, Rameez, Von Hausegger, Mohayaee, S.S. & Colin, *ApJL* **908**:L51,2021

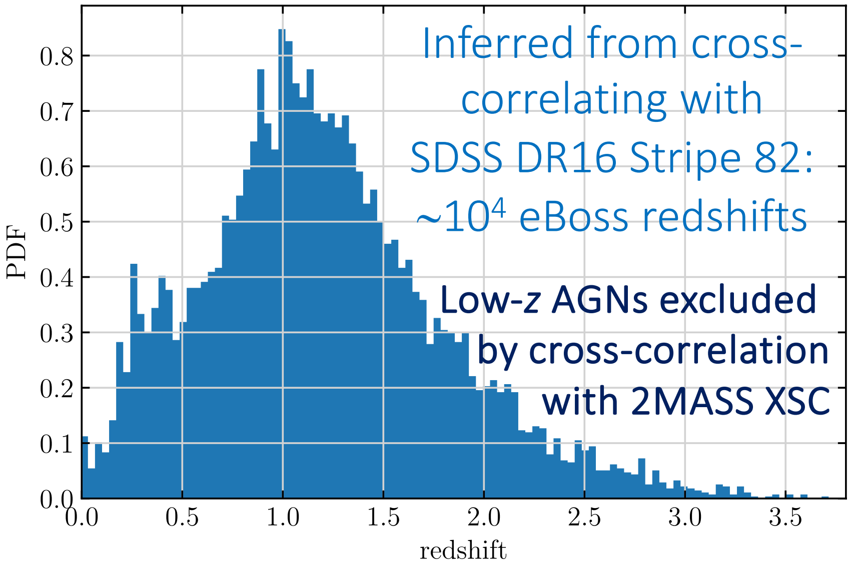

3.4 μm (W1)

4.6 μm (W2)

$W1 - W2 \geq 0.8$

$9 > W1 > 16.4$



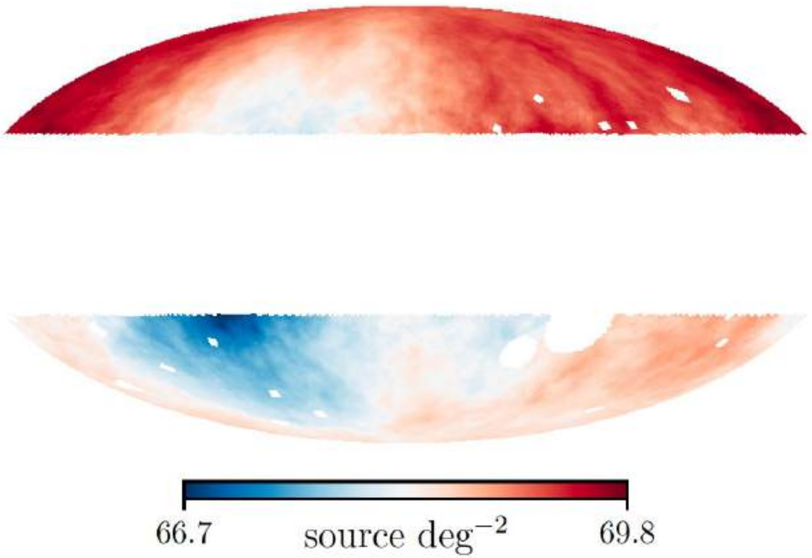

Inferred from cross-correlating with SDSS DR16 Stripe 82: ~10^4 eBoss redshifts

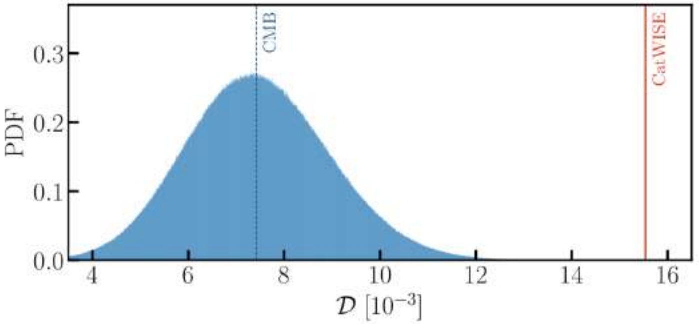
Low-z AGNs excluded by cross-correlation with 2MASS XSC

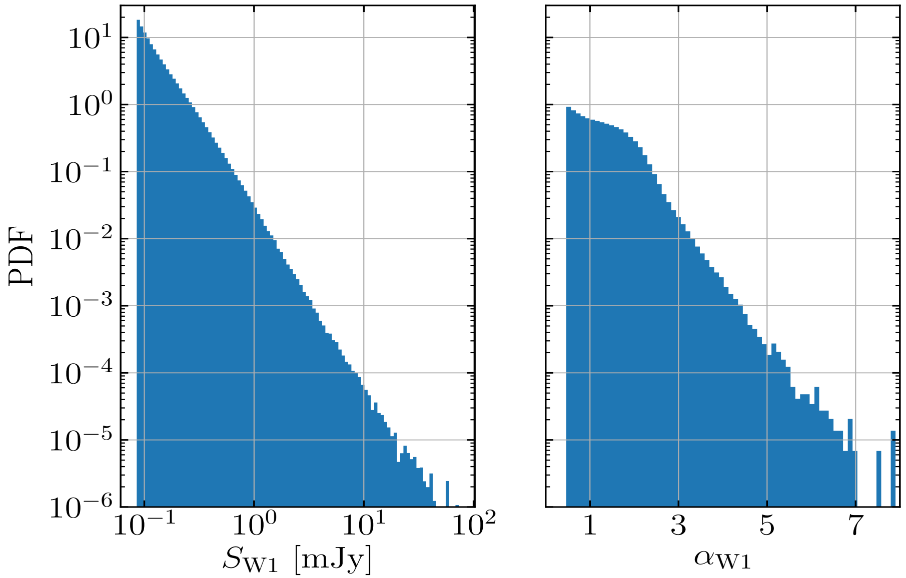
1.36 million high redshift quasars (99% with $z > 0.1$)

Now compare dipole to that predicted by E&B, given the spectrum and flux distribution

The direction is consistent with the CMB dipole – but the amplitude is x2 higher ↷

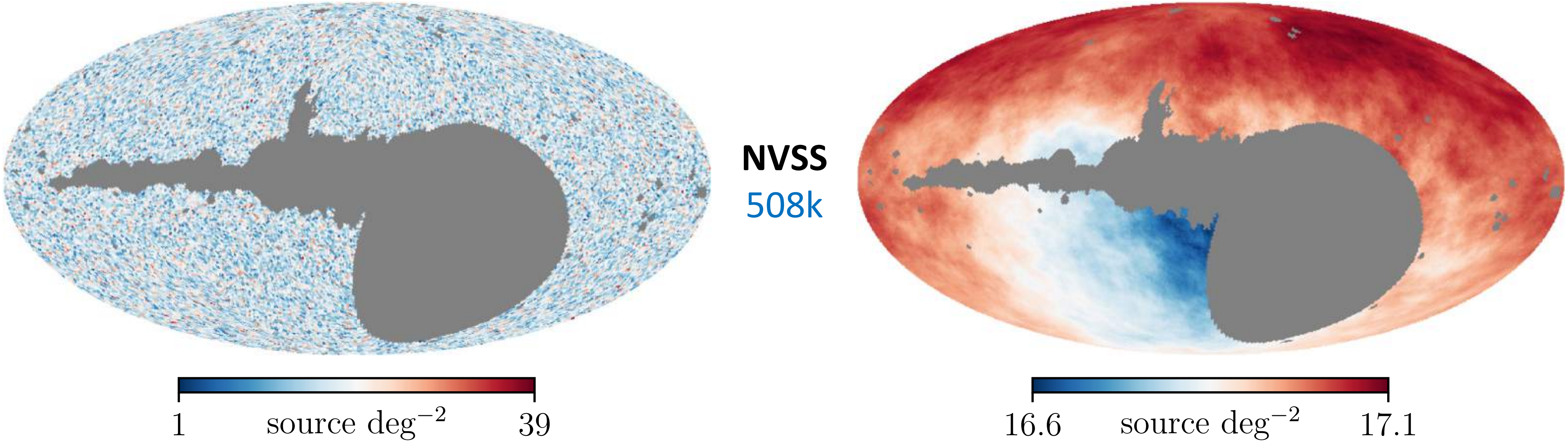






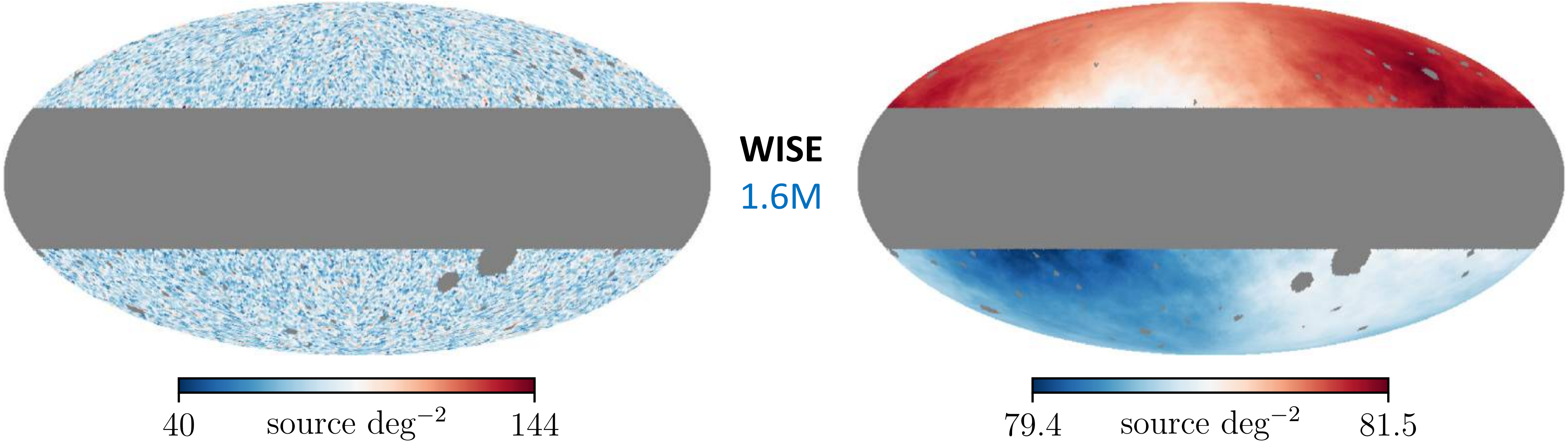
The kinematic interpretation of the CMB dipole is *rejected* with $p = 5 \times 10^{-7} \Rightarrow 4.9\sigma$

WE HAVE FURTHER CLEANED THE NVSS & WISE AGN CATALOGUES OF A VARIETY OF SYSTEMATICS



NVSS
508k

The two dipoles are *consistent*; vector mean: $D = (1.40 \pm 0.13) \times 10^{-2}$ towards (l, b) = (233.0,+34.4)

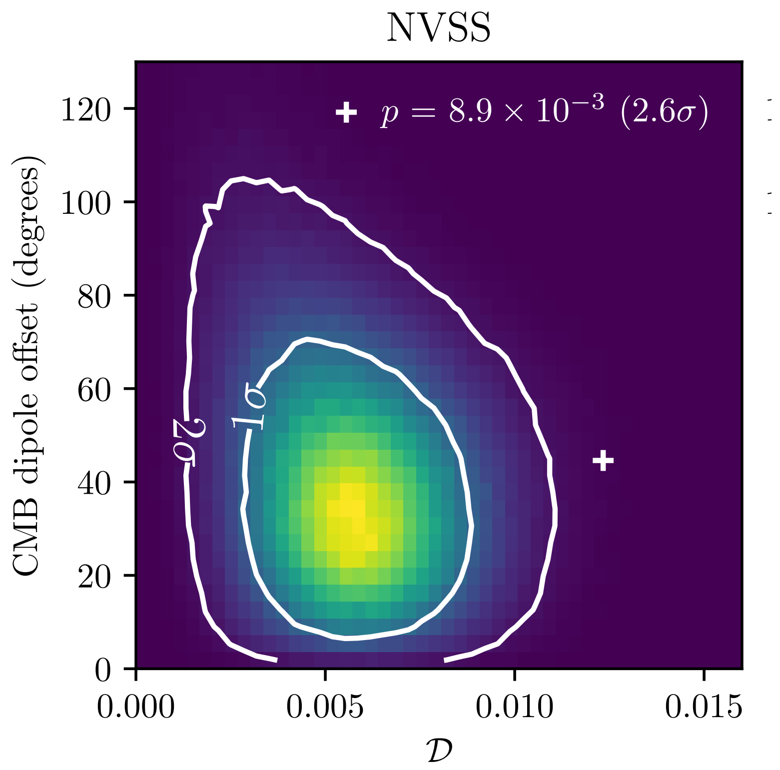


WISE
1.6M

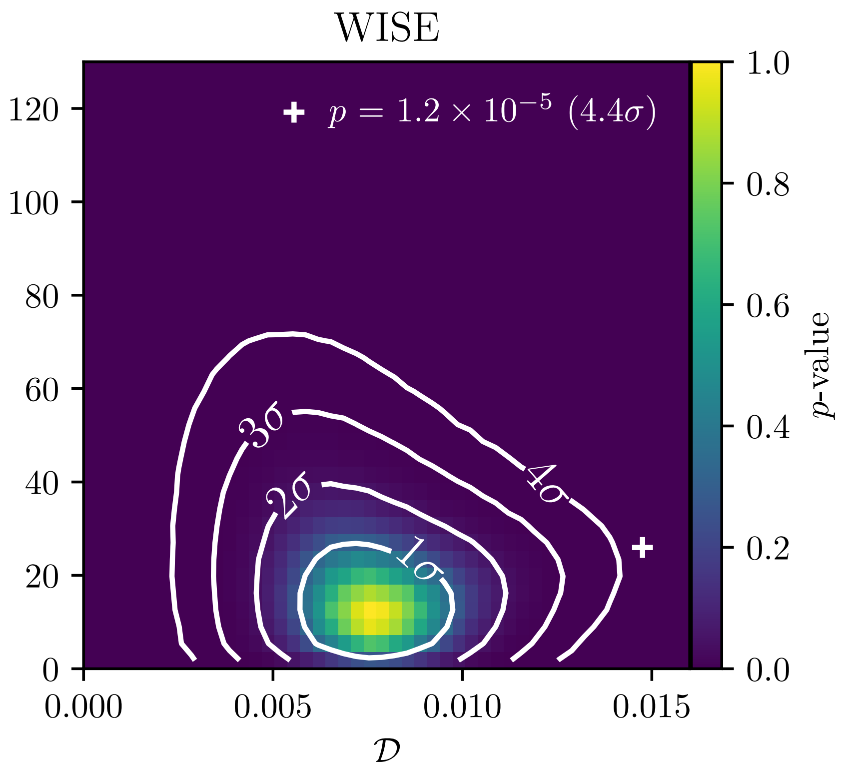
The agreement *improves* if we first subtract out the CMB dipole (assumed kinematic) from both

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

SINCE THE NVSS & WISE AGN CATALOGUES ARE *INDEPENDENT*, WE CAN COMBINE THE P-VALUES BY WHICH EACH REJECTS THE NULL HYPOTHESIS



Distribution of CMB dipole offsets and 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 *p*-values



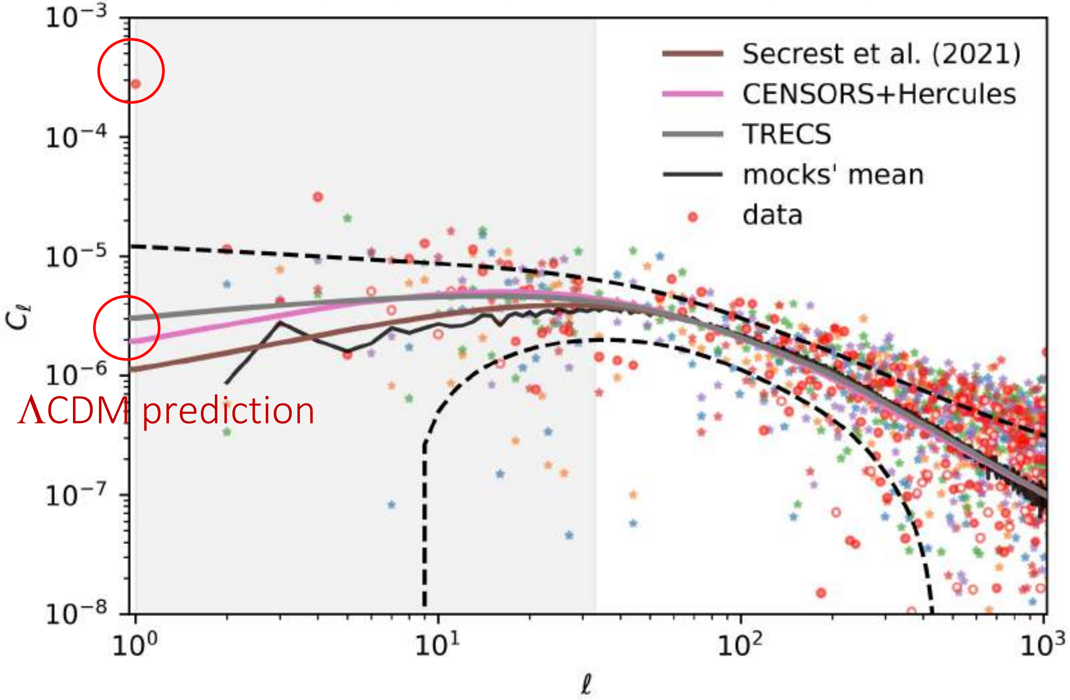
Combined significance ⇒ standard cosmology expectation is rejected at 5.1**σ**

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

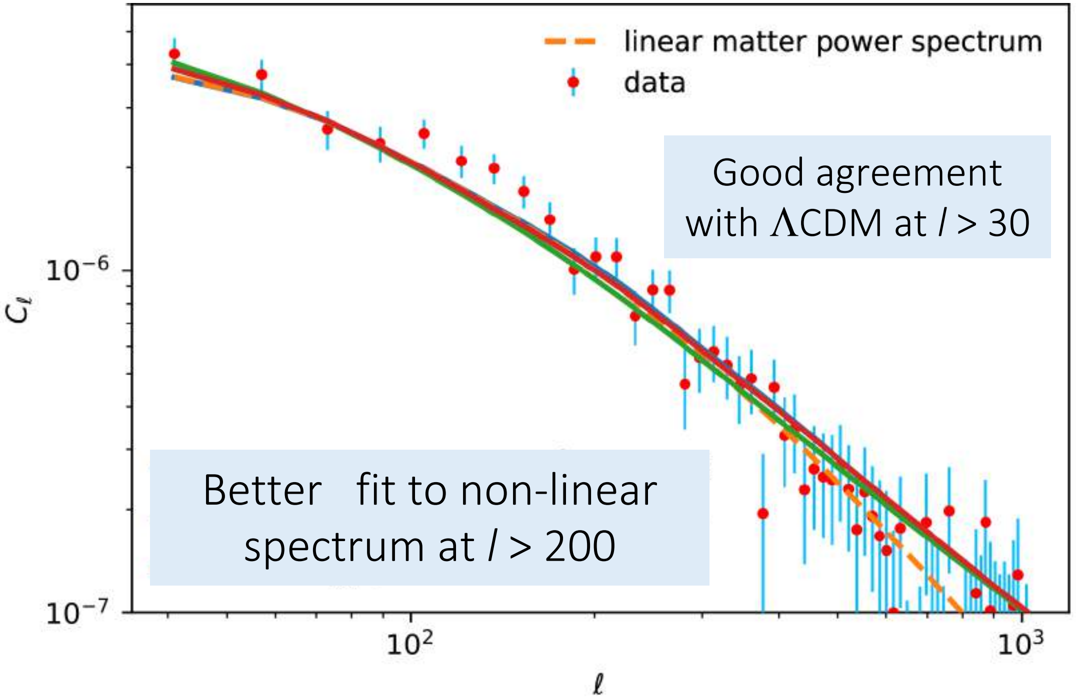
- This is *not* a nearby (clustering) dipole … Tiwari, Zhang & Nusser (*ApJ* **943**:116,2023) directly fit the CatWISE angular power spectrum to the ΛCDM expectation and find it to be ~19 times smaller than the observed dipole

- This result is *independent* of statistical method used … Dam, Lewis & Brewer (*MNRAS* **525**:231,2023) analyse the CatWISE catalogue by Bayesian means and report rejection of the standard cosmology with a significance of 5.7σ

THE CLUSTERING PROPERTIES OF AGNS/QUASARS IN THE CATWISE2020 CATALOG

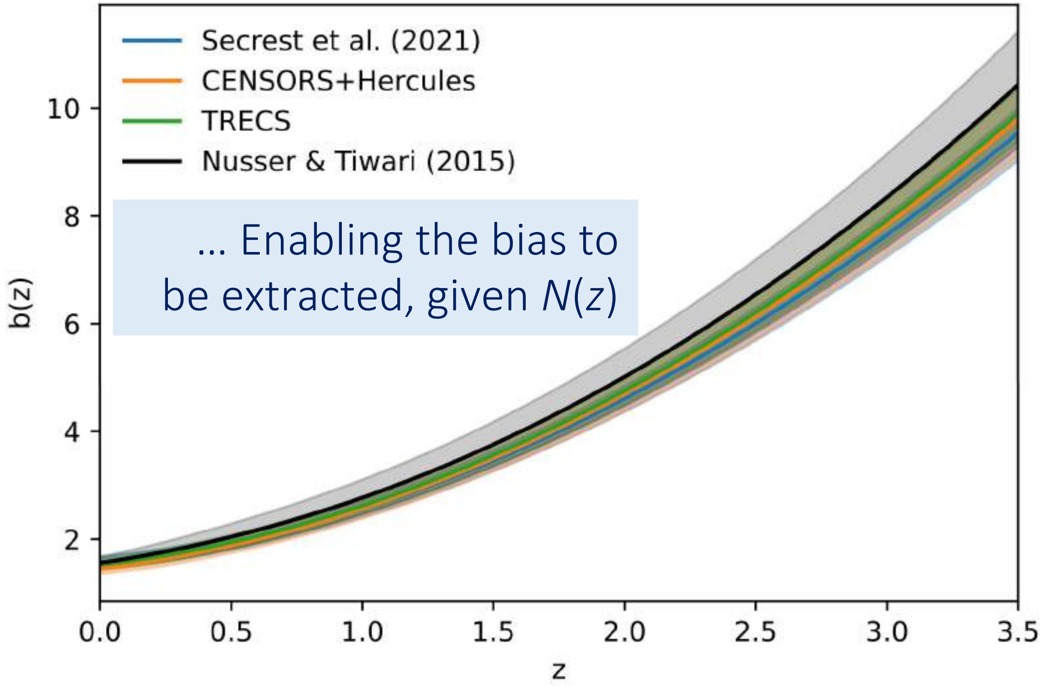


ΛCDM prediction

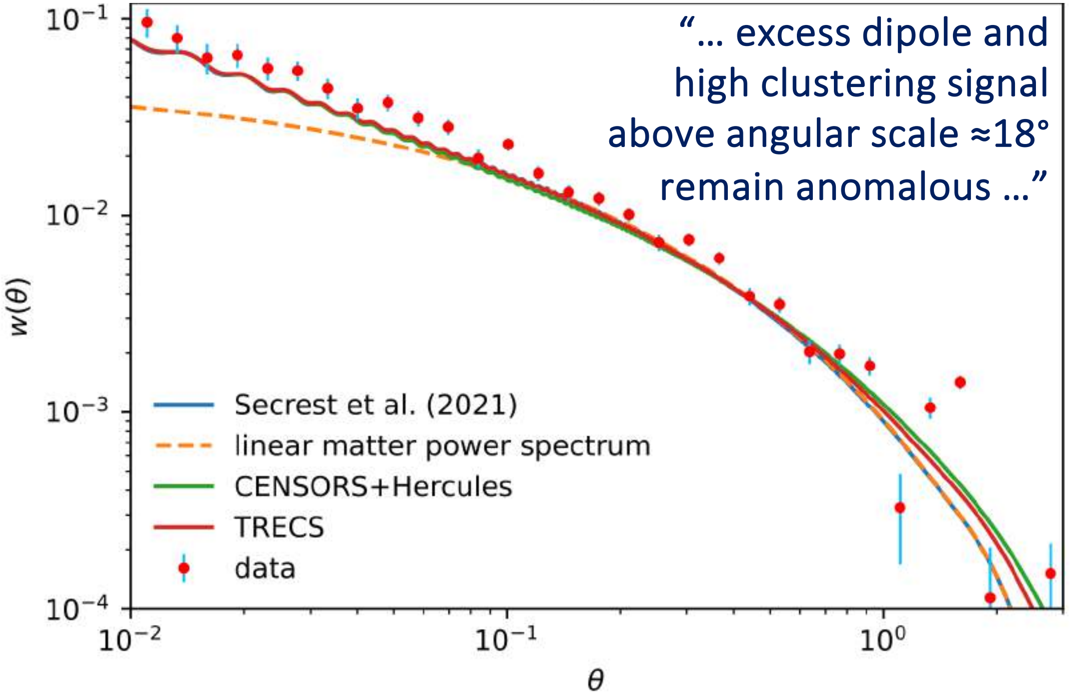


Good agreement with ΛCDM at $l > 30$

Better fit to non-linear spectrum at $l > 200$



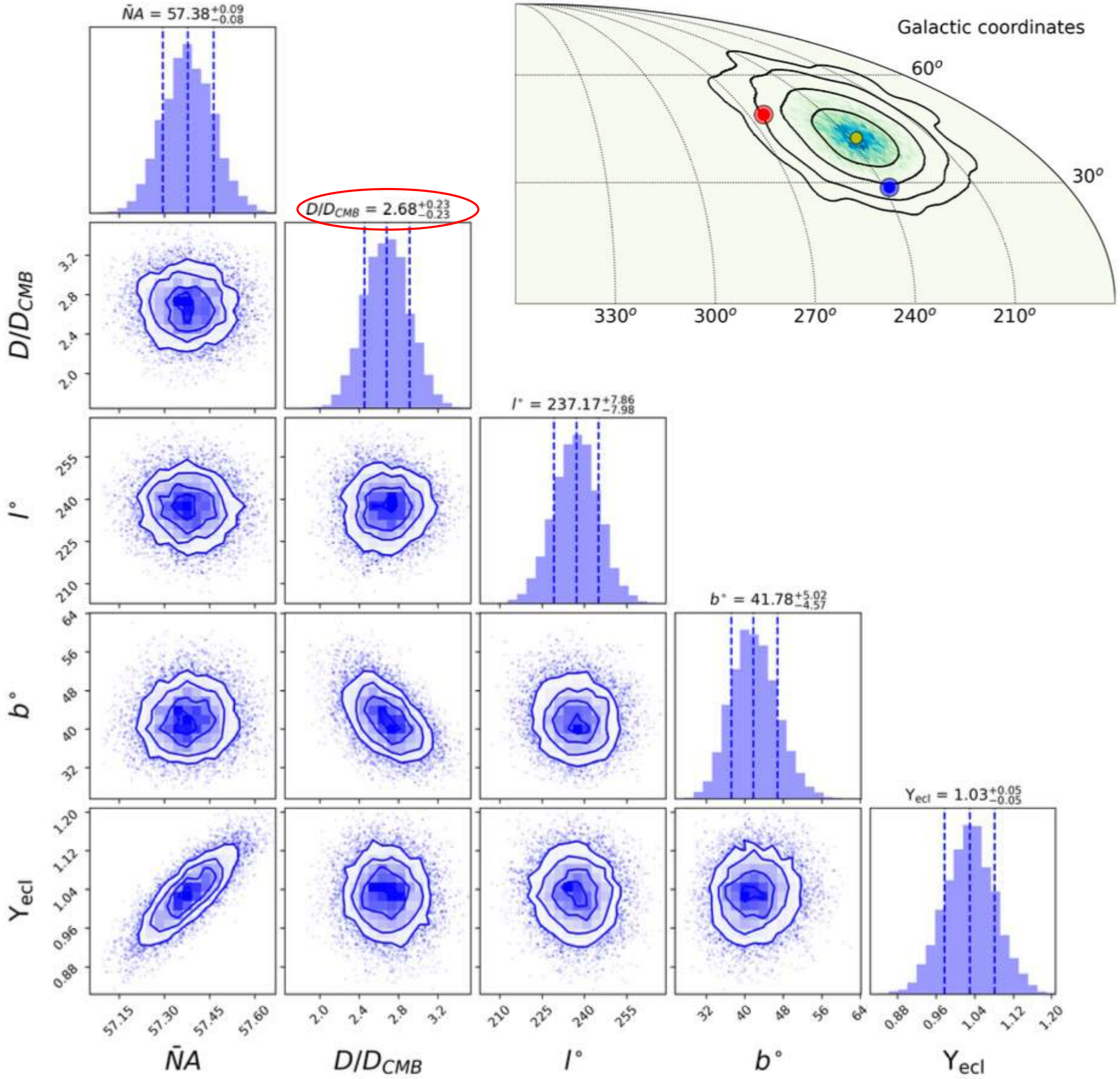
… Enabling the bias to be extracted, given $N(z)$



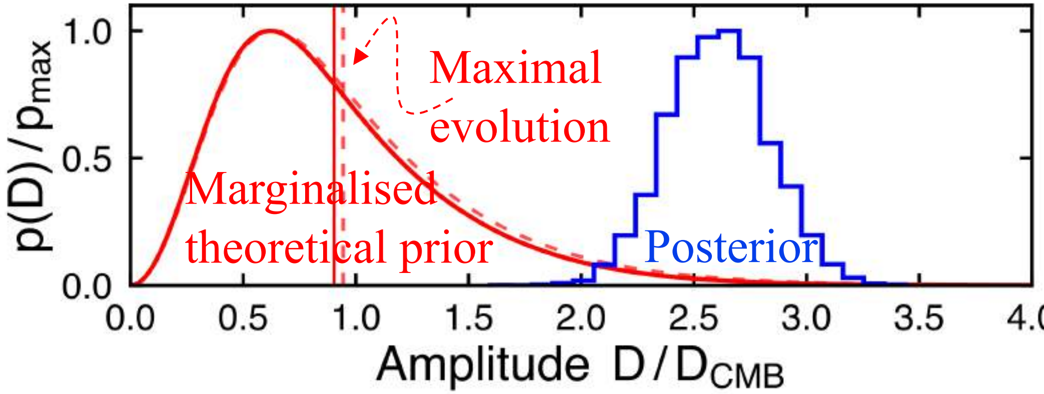
"… excess dipole and high clustering signal above angular scale ≈18° remain anomalous …"

Tiwari, Zhang & Nusser (*ApJ* **943**:116,2023)

TESTING THE COSMOLOGICAL PRINCIPLE WITH CATWISE QUASARS: A BAYESIAN ANALYSIS OF THE NUMBER-COUNT DIPOLE



A recent analysis of 1.36 million infrared-selected quasars has identified a significant tension in the amplitude of the number-count dipole compared to that derived from the CMB, thus challenging the Cosmological Principle. Here we present a Bayesian analysis of the same quasar sample, testing various hypotheses using the Bayesian evidence. We find unambiguous evidence for the presence of a dipole in the distribution of quasars with a direction that is consistent with the dipole identified in the CMB. However, the amplitude of the dipole is found to be 2.7 times larger than that expected from the conventional kinematic explanation of the CMB dipole, with a statistical significance of 5.7σ.



They demonstrate that any correlated evolution effects (Dalang & Bonvin 2021) can account for no more than 17% of D_{quasar}

Dam, Lewis, Brewer, MNRAS **525**:231,2023

The expected dipole can also be calculated in a General Relativistic framework

(Maartens, Clarkson & Chen, JCAP 01:013,2018; Nadolny, Durrer, Kunz & Padmanabhan, JCAP 11:009,2021)

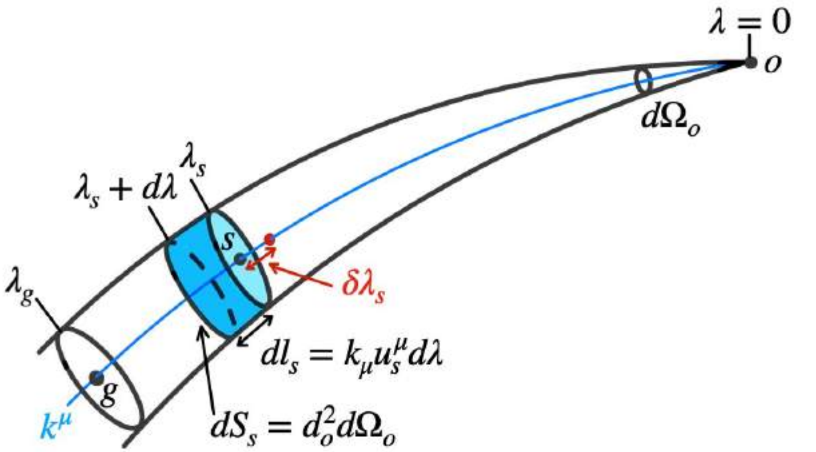


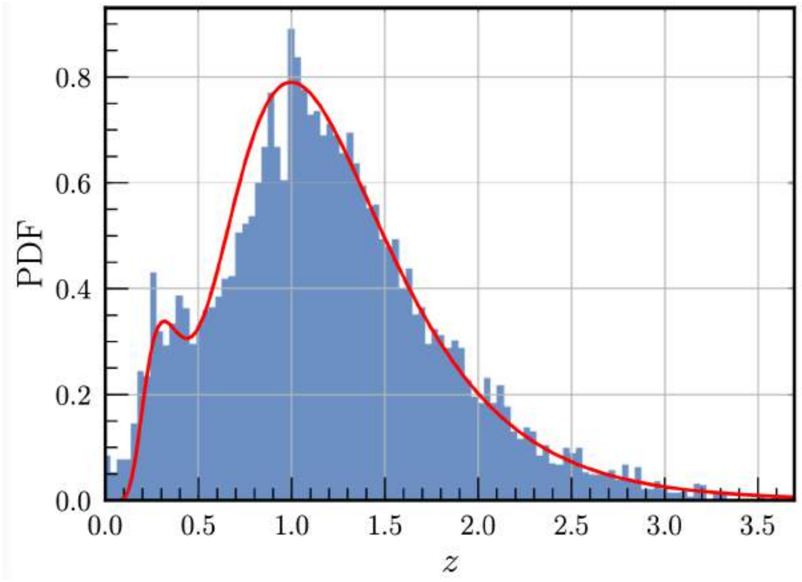
FIG. 1. A source at s emits photons which reach us at o along null geodesics k^μ parameterised by the affine parameter λ. Due to the source velocity u_s^μ, the photon has a spatial displacement dl_s following an infinitesimal change in the affine parameter $d\lambda$. The observed infinitesimal volume is $dV_s = dl_s dS_s$ and the cross-section dS_s of the photon bundle defines the Observer's area distance d_o. A fixed affine parameter λ_s hypersurface is related to a fixed redshift z hypersurface by shifting the affine parameter of the source by $\delta\lambda_s$. There may also be another source g beyond s. The total number count N per solid angle at o is the integral along the whole photon bundle. (After Figure 8 in Ellis [74].)

$$d_{\mathcal{N}}^{\rm kin} = \frac{1}{\int_0^{\lambda_s} \mathcal{N}_s(\lambda, L) r^2 d\lambda} \int_0^{\lambda_s} \left(2 + x(1+\alpha) + \frac{1}{\mathcal{H}} \frac{d}{d\lambda} \ln\left(\frac{r^2 \mathcal{N}_s}{\mathcal{H}} \right) \right) \beta \mathcal{N}_s(\lambda, L) r^2 d\lambda$$

$$= \underbrace{(2 + x(1+\alpha))\,\beta}_{\text{Ellis \& Baldwin (1984)}} + \boxed{\frac{1}{\int_0^{\lambda_s} \mathcal{N}_s(\lambda, L) r^2 d\lambda} \frac{r_s^2 \mathcal{N}_s}{\mathcal{H}_s} \beta}.$$

where, $\hat{\mathcal{N}}_s(z, F > F_*) = \int_{L_s(z,F)}^{\infty} dL\, \hat{n}_s(z, \ln L)$

Now plugging in $N(z)$ for the CatWISE catalogue



We find that the correction term is <0.001β, so the Ellis & Baldwin (1984) formula is quite accurate!

Dalang and Bonvin (*MNRAS* 512:3895,2022) suggest there may be *correlated* redshift evolution of x and α which enhances the expected dipole, but this can be at most 17% of $d^{\rm kin}$; moreover *no* evidence for such evolution is seen in CatWISE.

Domenech, Mohayaee, Patil & S.S., *JCAP* 10:019,2022

Anomalies in physical cosmology

P.J.E. Peebles

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

Received 9 August 2022, Accepted 21 October 2022

The evidence to be reviewed here is that the dipole anisotropy in the distribution of objects at distances comparable to the Hubble length is about in the direction expected from the kinematic effect if the dipole anisotropy in the CMB is due to our motion relative to the rest frame defined by the mean mass distribution, but the dipole amplitude is at least twice the prediction. **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.)

Annals Phys. **447**:169159,2022

This mismatch of the CMB and matter frames is motivating interesting attempts at explanation

Dipole Cosmology: The Copernican Paradigm Beyond FLRW
Chethan Krishnan, Ranjini Mondol, M. M. Sheikh-Jabbari [arXiv:2209.14918]

QCD axion dark matter and the cosmic dipole problem
Chengcheng Han
[arXiv:2211.06912]

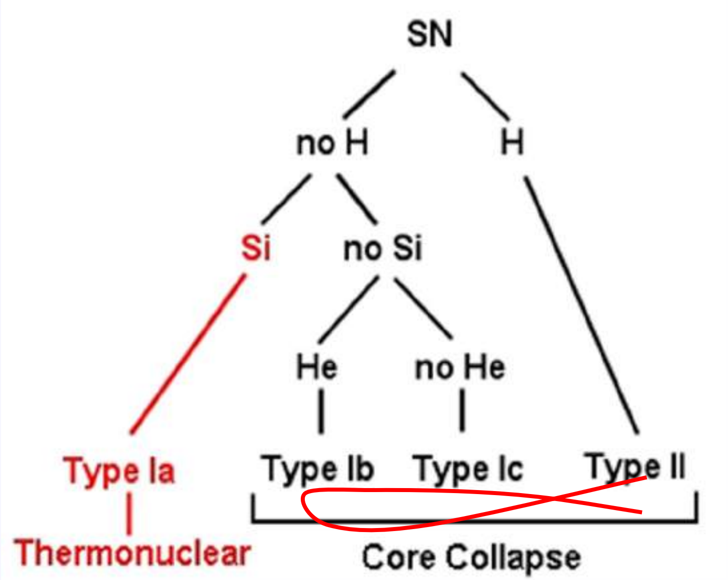
Large-scale geometry of the Universe
Yassir Awwad & Tomislav Prokopec [arXiv:2211.16893]

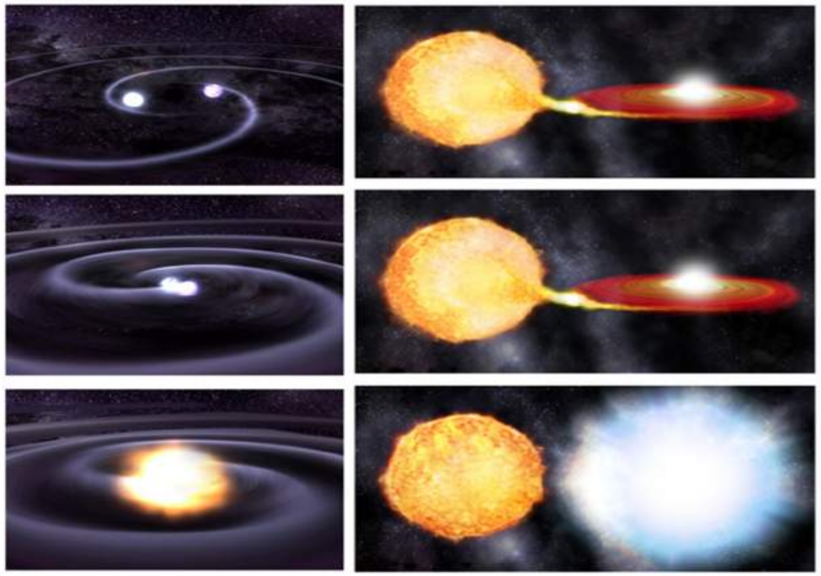
Spatially Homogeneous Universes with Late-Time Anisotropy [arXiv:2212.03224]
Andrei Constantin, Thomas R. Harvey, Sebastian von Hausegger & Andre Lukas

Modelling the emergence of cosmic anisotropy from non-linear structures
[arXiv:2302.05715]
Theodore Anton & Timothy Clifton

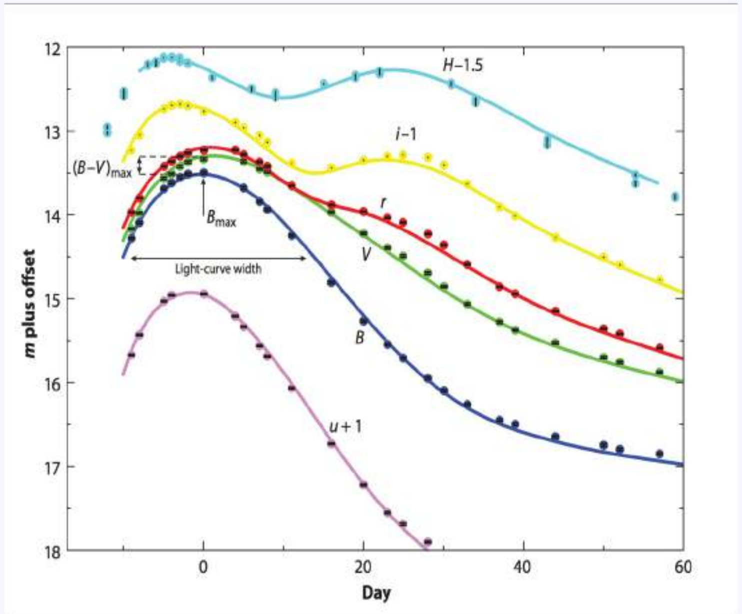
Anisotropic cosmology in the local limit of nonlocal gravity [arXiv:2308.08281]
Javad Tabatabaei, Abdolali Banihashemi, Shant Baghram & Bahram Mashhoon

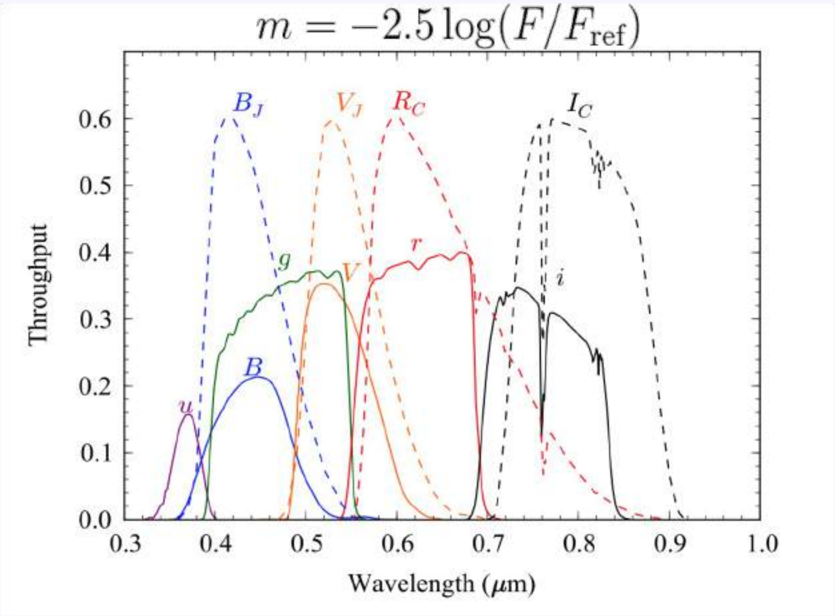
Cosmology with Type Ia supernovae





Goobar & Leibundgut, ARAA **61**:251,2011

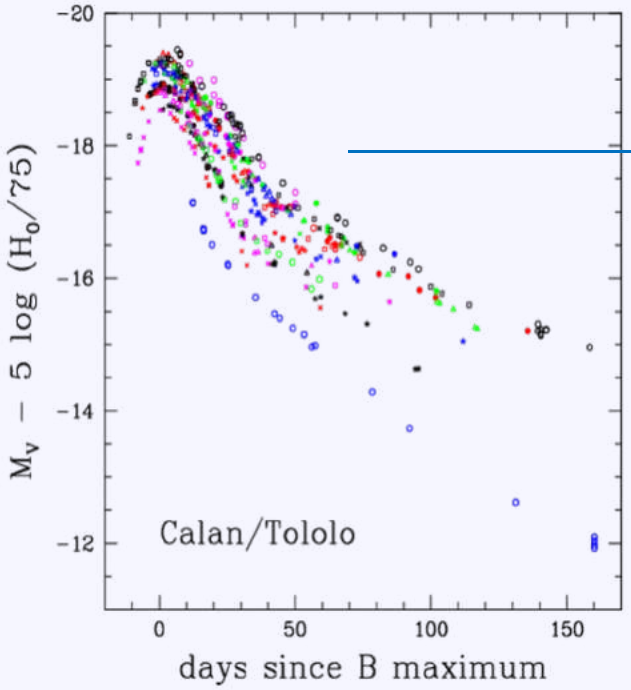




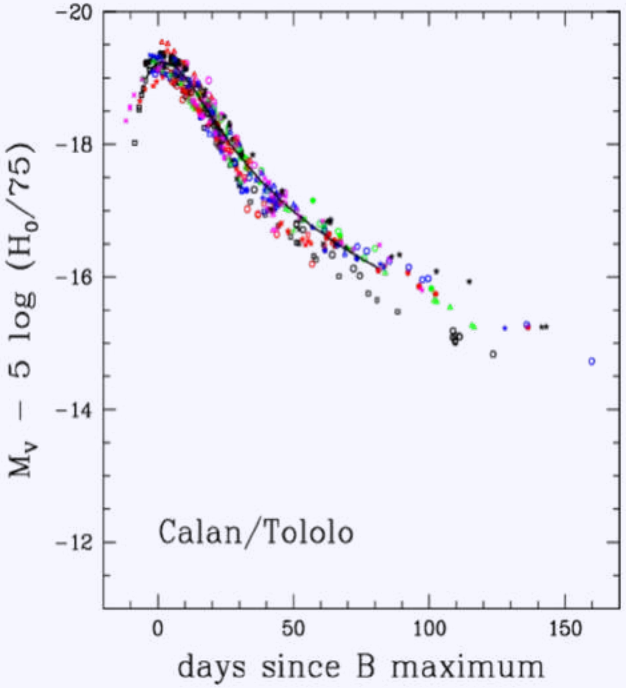
$$m = -2.5\log(F/F_{\rm ref})$$

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

Sn Ia are *not* ‘standard candles’



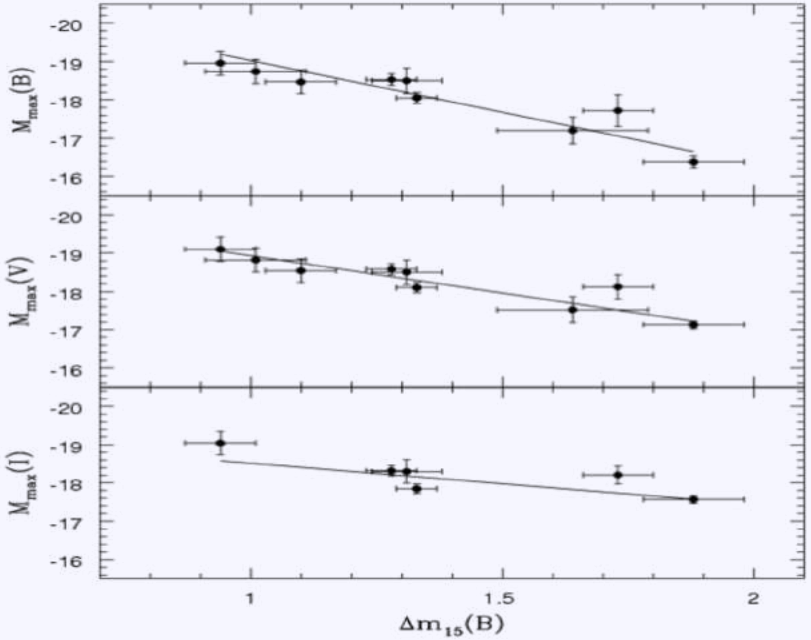
But they are ‘standardisable’



Hamuy, 1311.5099

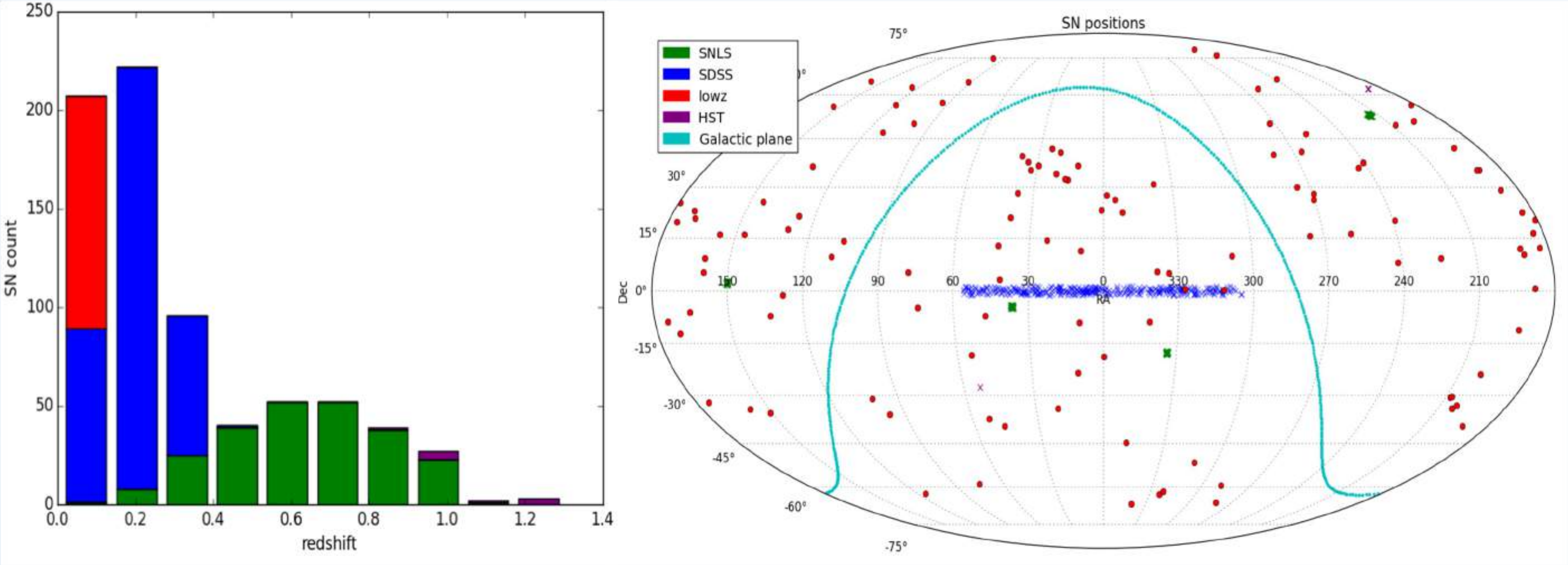
… using the observed correlation between peak magnitude and light curve width

(NB: this is empirical and *not* understood theoretically)



Phillips, ApJ 413:L105,1993

Joint Lightcurve Analysis catalogue (740 SNe Ia)

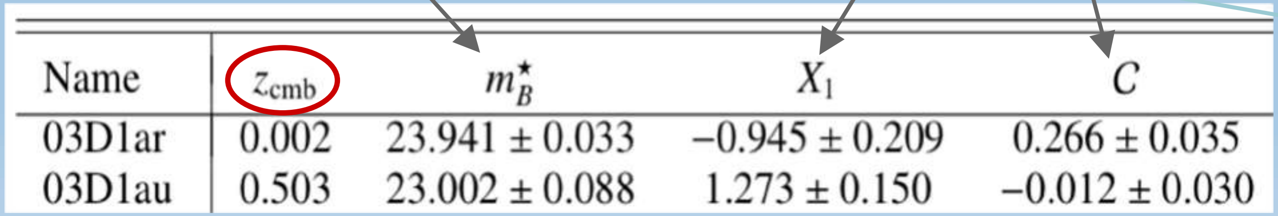


Betoule *et al*, A&A **568**:A22,2014

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

B-band

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



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

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

COSMOLOGY

Distance modulus

$$\mu \equiv 25 + 5\log_{10}(d_{\rm L}/{\rm Mpc}), \quad \text{where:}$$

$$d_{\rm L} = (1+z)\frac{d_{\rm H}}{\sqrt{\Omega_k}}\,{\rm sinn}\left(\sqrt{\Omega_k}\int_0^z \frac{H_0{\rm d}z'}{H(z')}\right),$$

$$d_{\rm H} = c/H_0, \quad H_0 \equiv 100h\ {\rm km\,s^{-1}Mpc^{-1}},$$

$$H = H_0\sqrt{\Omega_{\rm m}(1+z)^3 + \Omega_k(1+z)^2 + \Omega_\Lambda},$$

Luminosity distance

sinn → sinh for $\Omega_k > 0$ and sinn → sin for $\Omega_k < 0$

So the μ-z data enables extraction of the parameter combination: $\sim 0.8\ \Omega_\Lambda - 0.6\ \Omega_{\rm m}$
(NB: to determine H_0 requires knowing the *absolute* magnitude M ➛ "distance ladder")

COSMOGRAPHY

Acceleration is a *kinematic* quantity so data can also be analysed without assuming any dynamical model … by expanding the time variation of the scale factor in a Taylor series (e.g. Visser, CQG **21**:2603,2004) → good to <6% for JLA (extends to $z \sim 1.2$)

$q_0 \equiv -(\ddot{a}a)/\dot{a}^2$

$j_0 \equiv (\dddot{a}/a)(\dot{a}/a)^{-3}$

$$d_L(z) = \frac{c\,z}{H_0}\left\{1 + \frac{1}{2}\left[1 - q_0\right]z - \frac{1}{6}\left[1 - q_0 - 3q_0^2 + j_0 + \frac{kc^2}{H_0^2\,a_0^2}\right]z^2 + O(z^3)\right\}$$

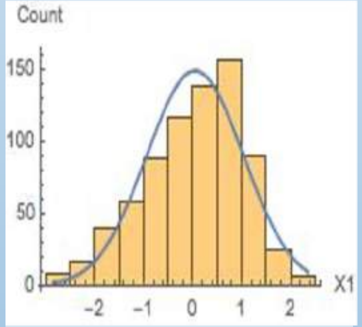
Supernova analyses use the 'adjusted chi-squared' method … wherein σ_{int} is *adjusted* to get χ^2 of 1/d.o.f. for the fit to the *assumed* ΛCDM model

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

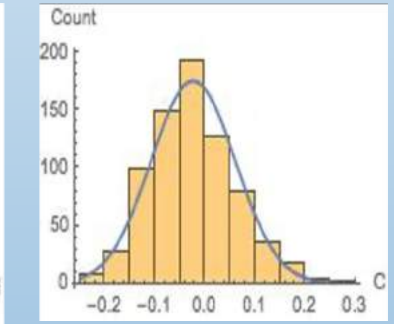
We employ a Maximum Likelihood Estimator … and get rather different results

Nielsen, Guffanti & S.S., Sci.Rep. **6**:35596,2016

… well-approximated as Gaussian



'Stretch' corrections



'Colour' corrections

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

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

$$p[(M, x_1, c)|\theta] = p(M|\theta)p(x_1|\theta)p(c|\theta), \quad \text{where:}$$
$$p(M|\theta) = (2\pi\sigma_{M_0}^2)^{-1/2} \exp\left\{-\left[(M - M_0)/\sigma_{M_0}\right]^2/2\right\},$$
$$p(x_1|\theta) = (2\pi\sigma_{x_{1,0}}^2)^{-1/2} \exp\left\{-\left[(x_1 - x_{1,0})/\sigma_{x_{1,0}}\right]^2/2\right\},$$
$$p(c|\theta) = (2\pi\sigma_{c_0}^2)^{-1/2} \exp\left\{-\left[(c - c_0)/\sigma_{c_0}\right]^2/2\right\}.$$

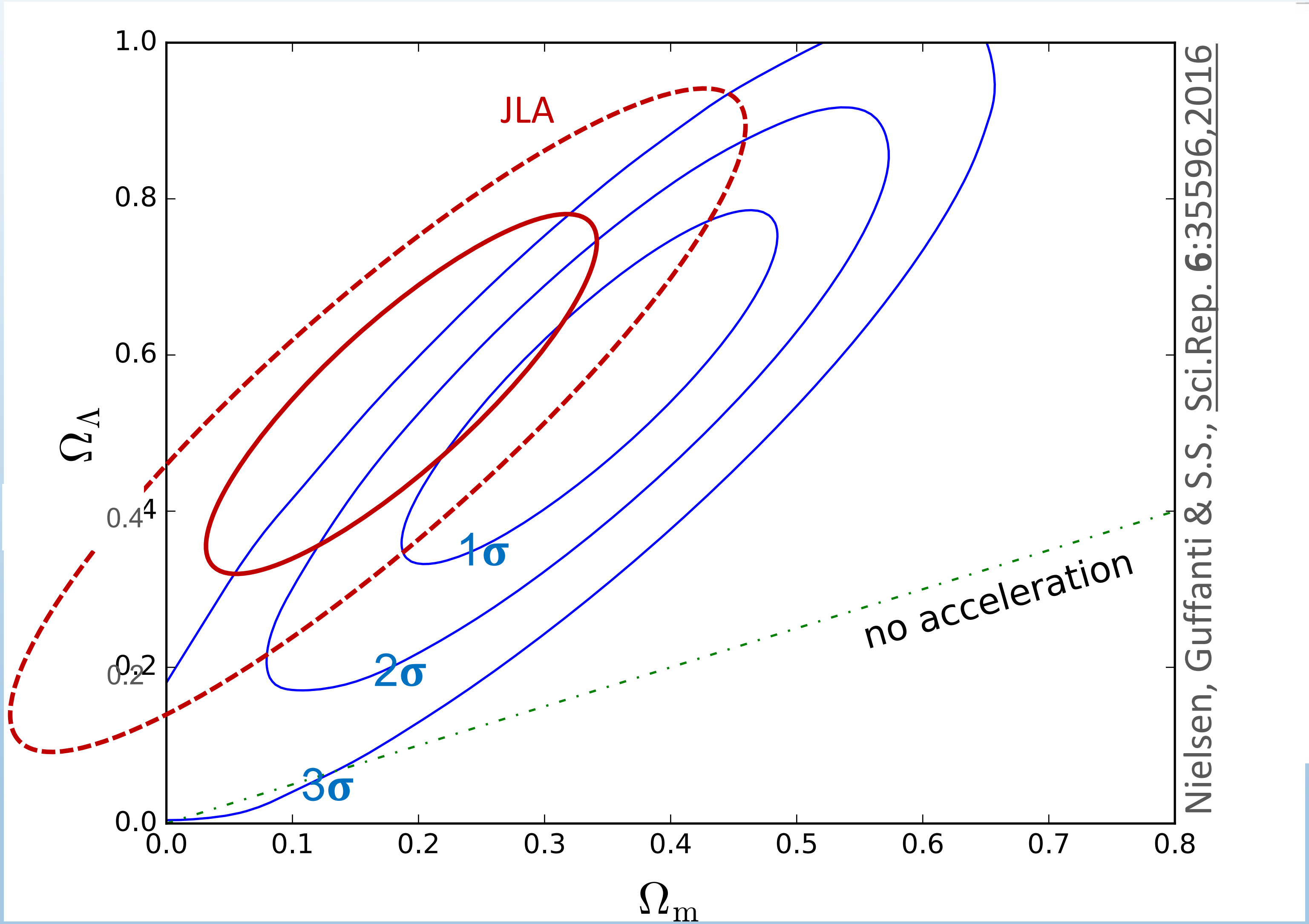
intrinsic distributions

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

cosmology

SALT2

AVERAGED OVER THE SKY, THE DATA IS CONSISTENT WITH AN UNIFORM EXPANSION RATE $(\Rightarrow \rho + 3p = 0)$



Nielsen, Guffanti & S.S., Sci.Rep. **6**:35596,2016

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*

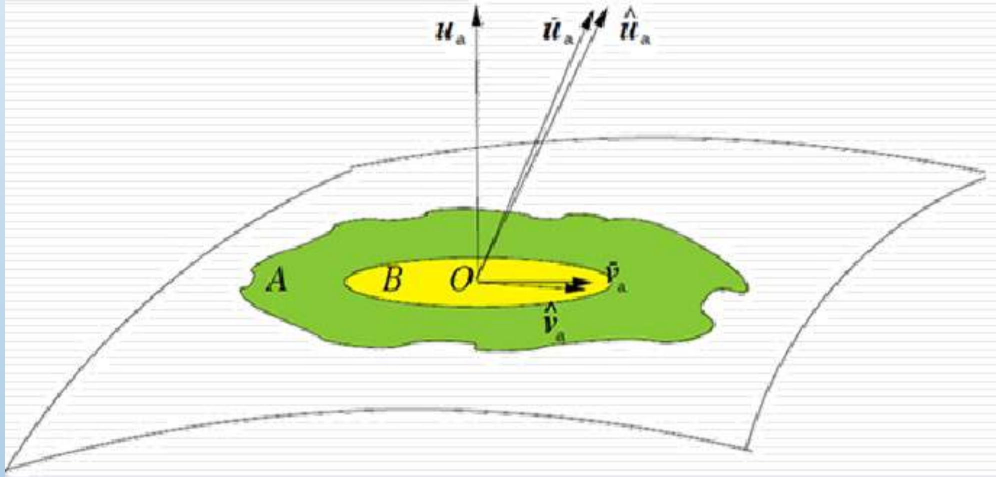
NB: We show the result in the $\Omega_{\rm m}$- Ω_Λ plane for comparison with previous results (JLA) simply to emphasise that the statistical analysis has *not* been done correctly earlier

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

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 direction of the bulk flow



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

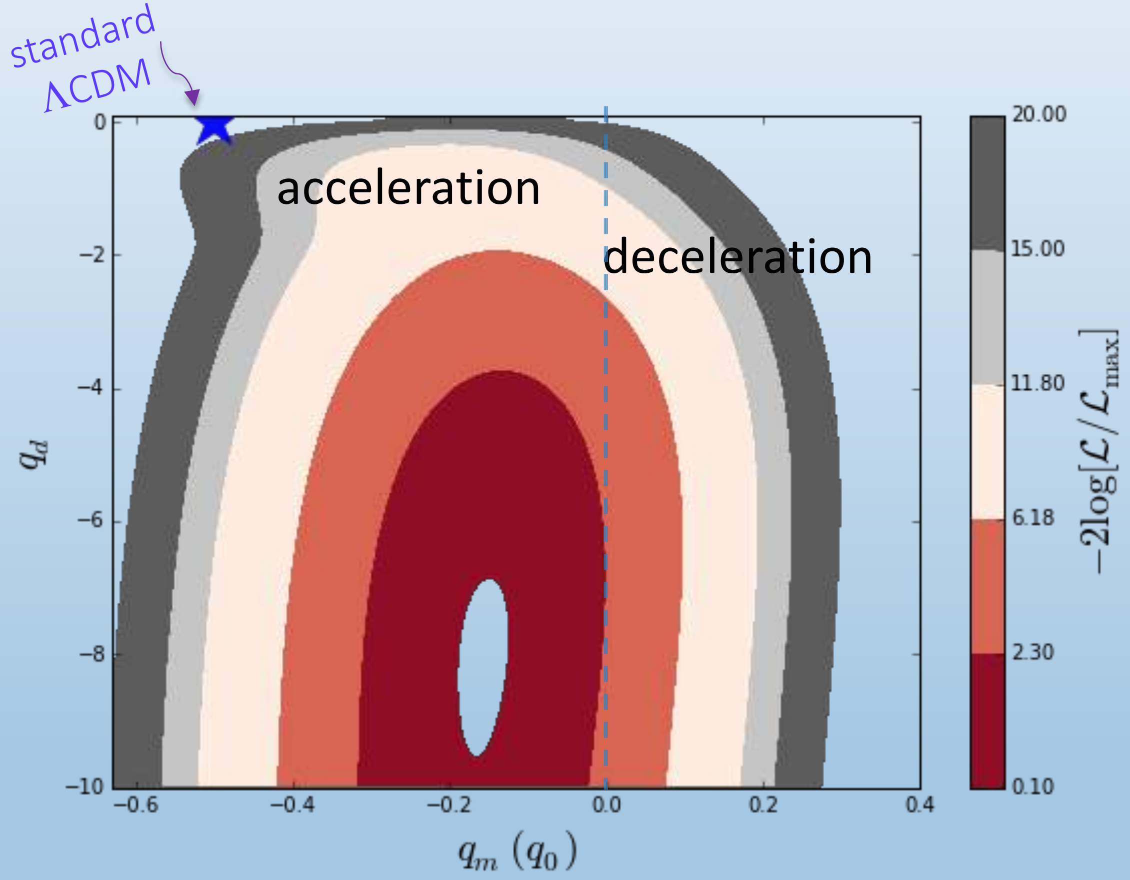
$$1 + \tilde{q} = (1 + q)\left(1 + \frac{\vartheta}{\Theta}\right)^{-2} - \frac{3\dot{\vartheta}}{\Theta^2}\left(1 + \frac{\vartheta}{\Theta}\right)^{-2}, \qquad \tilde{\Theta} = \Theta + \vartheta,$$

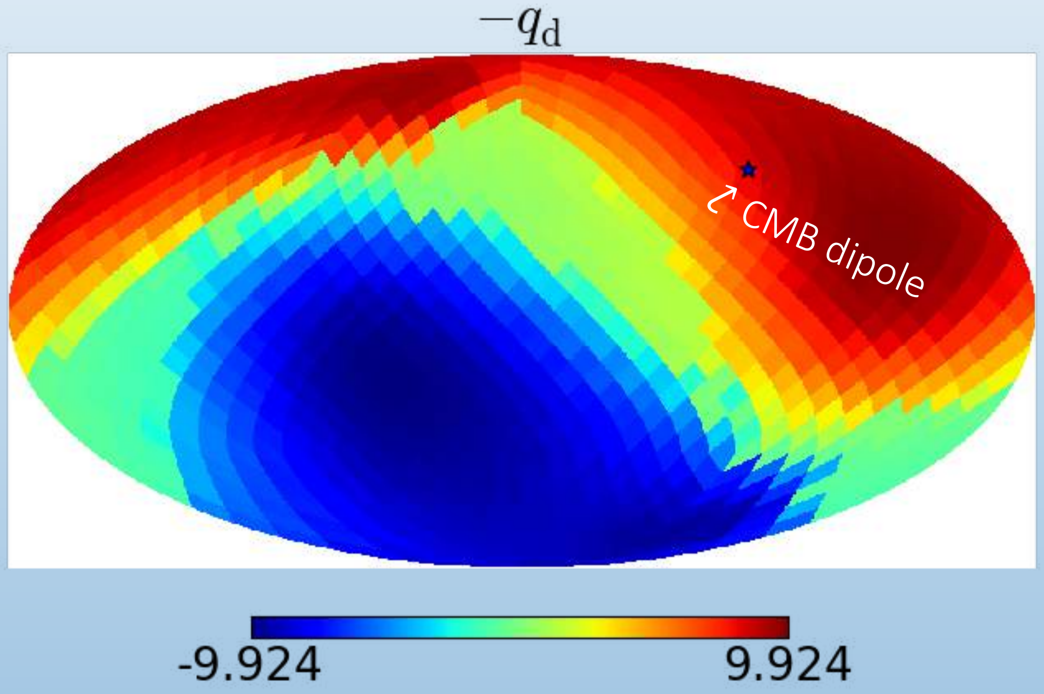
drops below 1 and the comoving observer 'measures' negative deceleration parameter

A cosmographic analysis of JLA Type Ia Supernova luminosity distances (in the heliocentric frame) shows that the inferred acceleration is indeed *aligned* with the local bulk flow

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

$$q_0 \equiv -(\ddot{a}a)/\dot{a}^2 \Longmapsto q_\mathrm{m} + \vec{q}_\mathrm{d}.\hat{n}\mathcal{F}(z, S)$$





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 suggests that cosmic acceleration is an artefact of our being located in a deep bulk flow … and *not* due to Λ

SUMMARY

➢ The ‘standard model’ of cosmology was established before there was any data …
its empirical foundations (homogeneity, isotropy) have not been rigorously 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‘

➢ We are in a ‘bulk flow’ which stretches out *beyond* the scale at which
the universe is supposed to become statistically homogeneous

The inference that the Hubble expansion rate is *accelerating* may be just an artefact
of this 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 FLRW metric assumption

We must begin again, to construct a new standard model of cosmology
(following the manifesto of Ellis & Stoeger, CQG 4:1697,1987 aka the ‘fitting problem‘)

Project 252: *Testing the isotropy of the universe*

- **Team lead:** Subir Sarkar **; Co-leads:** Sebastian von Hausegger, Mohamed Rameez
- **Members:** David Alonso, Farrukh Azfar, Eric Gawiser, Mustapha Ishak, Ian Shipsey, Jeff Tseng, Tony Tyson, … all are welcome to join in!
- **Abstract:**

We will test the assumption of isotropy underlying the FLRW metric, upon which the standard LCDM model is based.

- **Brief description:**

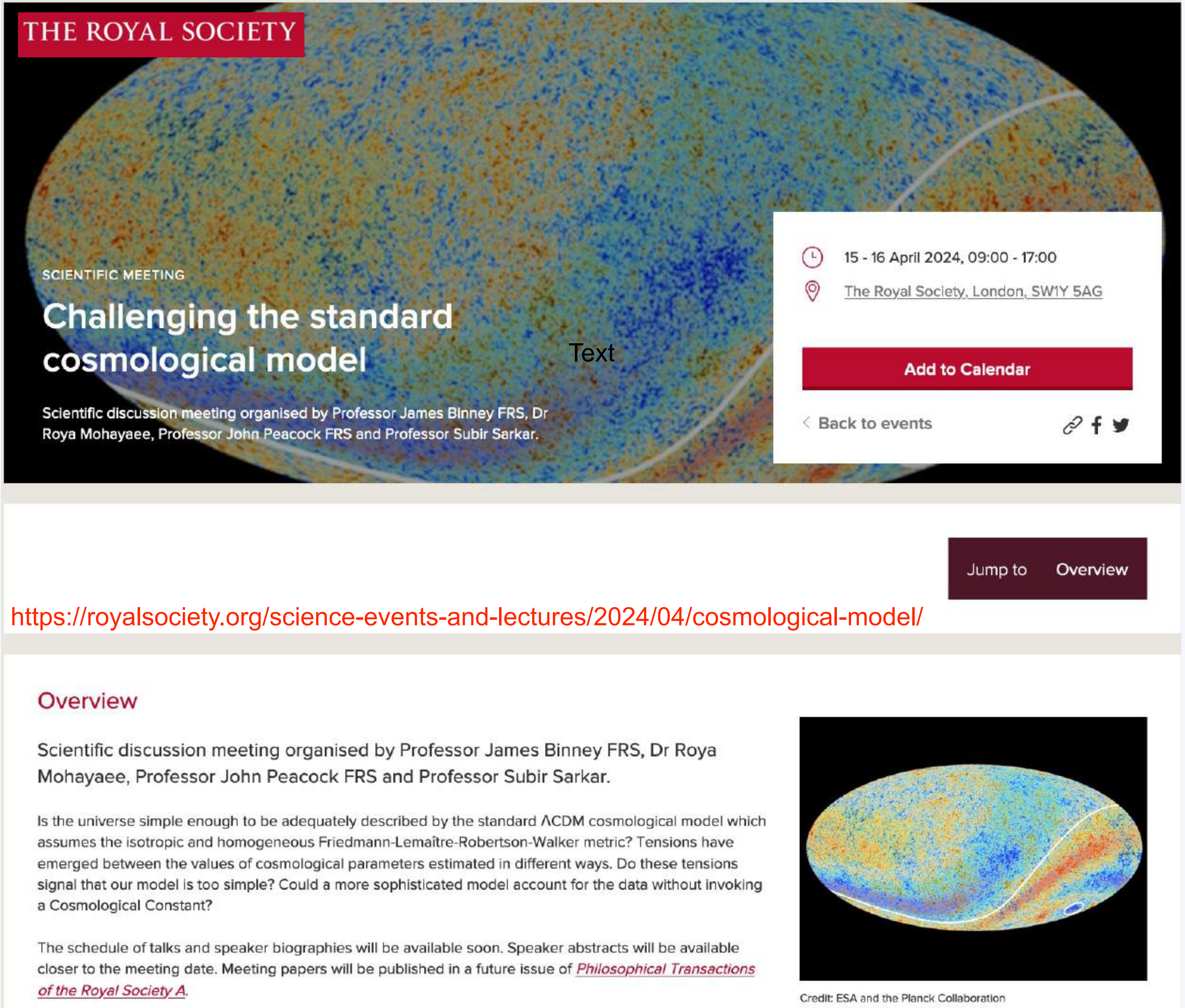
We will test if the matter distribution in the Universe is indeed statistically isotropic, justifying the use of the Friedmann-Lemaitre-Robertson-Walker metric. Dipole anisotropies in flux limited catalogues of sources at redshift > 0.1 will be used to determine, via the Ellis-Baldwin test, if the rest frames of matter and radiation indeed coincide on large scales as is required by the Cosmological Principle. Our analyses will extend existing data pipelines for model dependence, and develop alternative pipelines as necessary. We will make forecasts and/or simulated analyses which evaluate the prospect of using LSST galaxy samples to measure the kinematic dipole. Subsequently we will use the Y1+ data to test recent claims of an anomalously large matter dipole which violate the Cosmological Principle.

- **Associated DESC Projects:**

253: *Testing the homogeneity of the cosmic matter field* (**Team lead:** Sebastian von Hausegger)

254: *Testing tilted cosmology* (**Team lead:** Mohamed Rameez)

- **Working Groups involved:** MCP



SCIENTIFIC MEETING

Challenging the standard cosmological model

Scientific discussion meeting organised by Professor James Binney FRS, Dr Roya Mohayaee, Professor John Peacock FRS and Professor Subir Sarkar.

15 - 16 April 2024, 09:00 - 17:00

The Royal Society, London, SW1Y 5AG

Text

https://royalsociety.org/science-events-and-lectures/2024/04/cosmological-model/

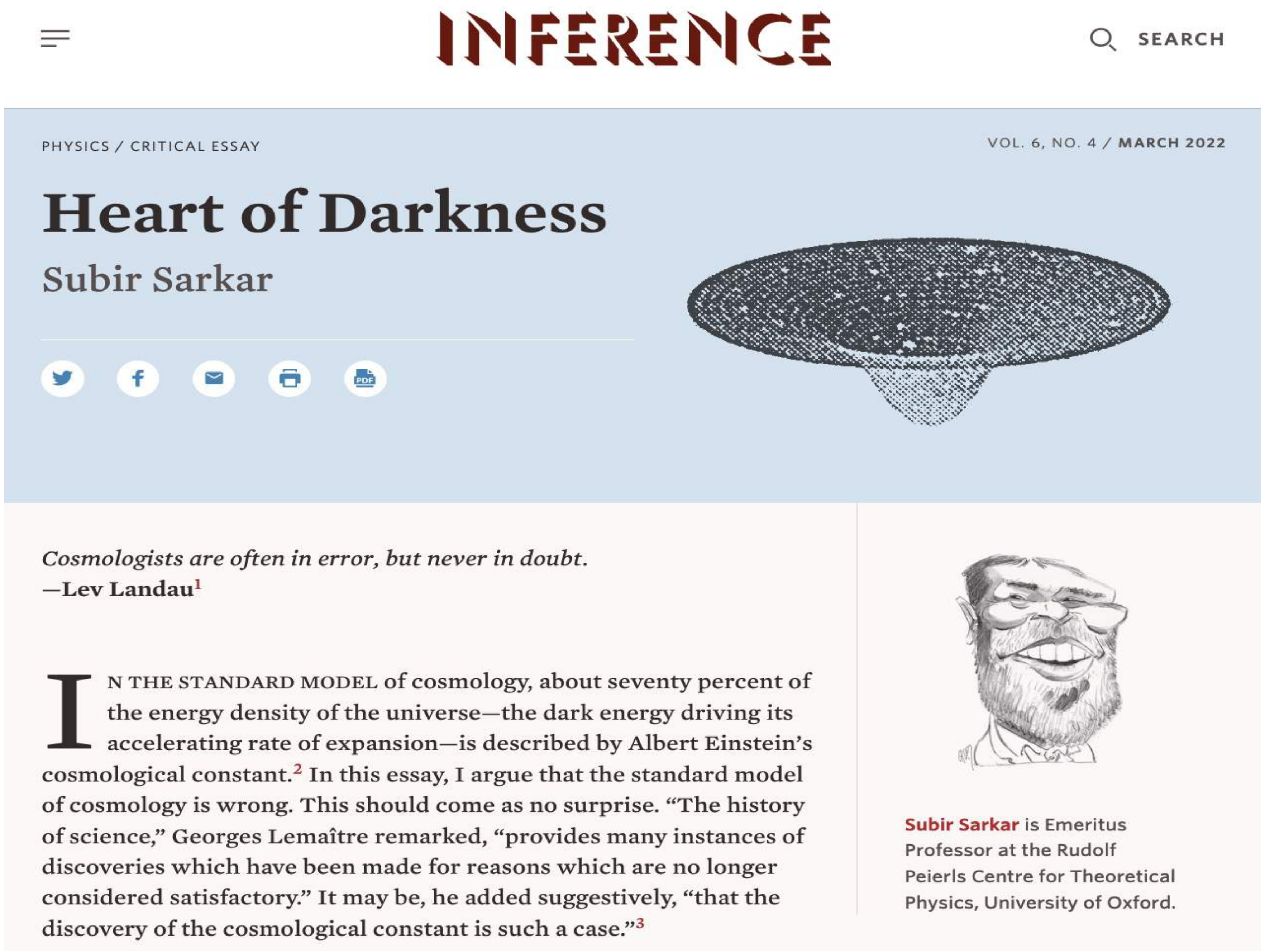
Overview

Scientific discussion meeting organised by Professor James Binney FRS, Dr Roya Mohayaee, Professor John Peacock FRS and Professor Subir Sarkar.

Is the universe simple enough to be adequately described by the standard ΛCDM cosmological model which assumes the isotropic and homogeneous Friedmann-Lemaître-Robertson-Walker metric? Tensions have emerged between the values of cosmological parameters estimated in different ways. Do these tensions signal that our model is too simple? Could a more sophisticated model account for the data without invoking a Cosmological Constant?

The schedule of talks and speaker biographies will be available soon. Speaker abstracts will be available closer to the meeting date. Meeting papers will be published in a future issue of *Philosophical Transactions of the Royal Society A*.

Credit: ESA and the Planck Collaboration



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]

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