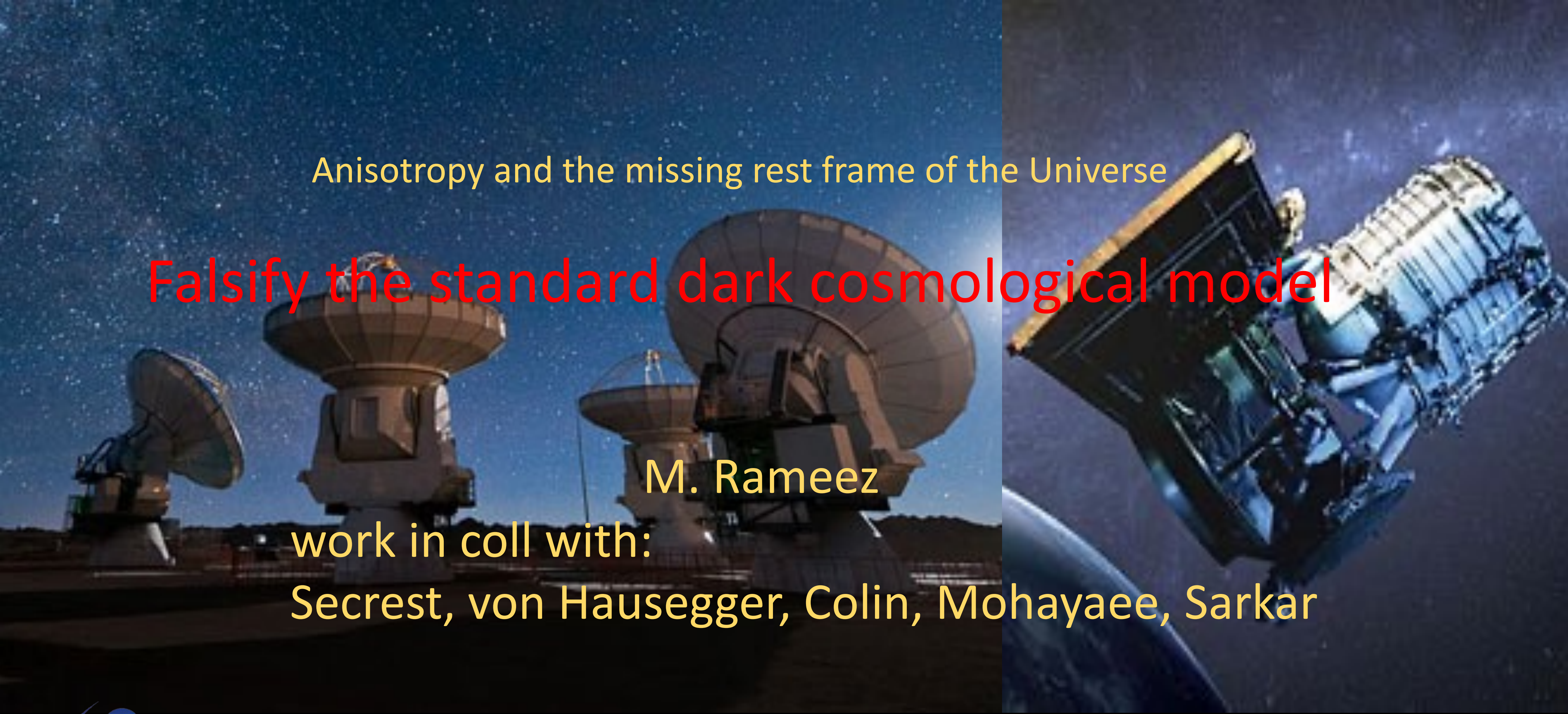


Anisotropy and the missing rest frame of the Universe

Falsify the standard dark cosmological model

M. Rameez

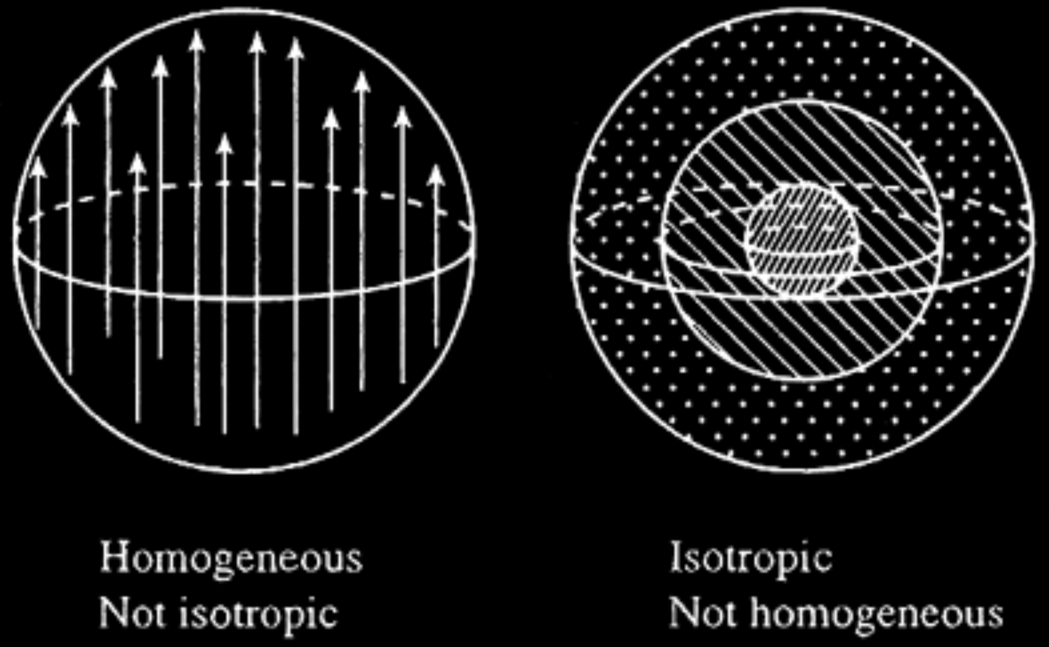
work in coll with:
Secrest, von Hausegger, Colin, Mohayaee, Sarkar

tifr

PPC 2024
IIT Hyderabad
17th October 2024

The cosmological principle

The Universe is (statistically) isotropic and homogenous (on large scales).



No special positions or directions in the Universe.
"The universe presents the same general aspect at every point"
Edward Arthur Milne
Also the Copernican principle : we are 'typical' observers.

THE 'PERFECT' VERSION WAS ABANDONED FOLLOWING THE DISCOVERY OF THE CMB IN 1964 AND THE REALIZATION THAT THE UNIVERSE *DOES* HAVE A BEGINNING ... BUT THE COSMOLOGICAL PRINCIPLE LIVED ON

Enables an enormous simplification in the equations

Einstein Field Equations - > Friedmann Equations

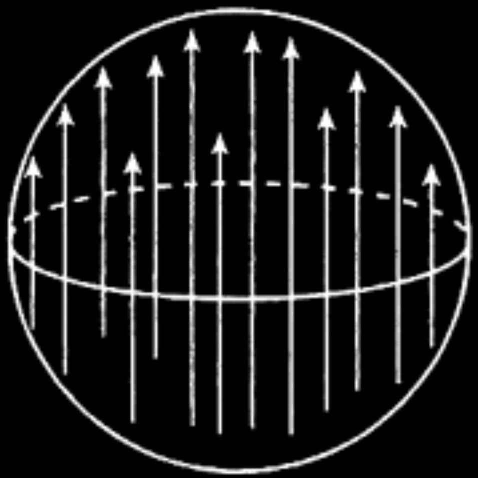
Scale factor a(t)

$$\Omega_M + \Omega_K + \Omega_\Lambda = 1$$

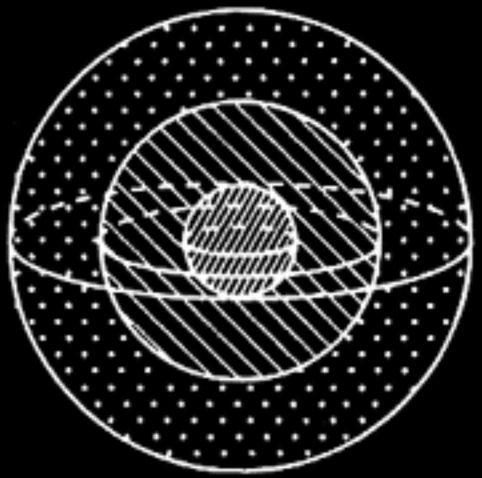
The cosmic sum rule

The cosmological principle

The Universe is sensibly isotropic and homogenous when averaged on large scales



Homogeneous
Not isotropic



Isotropic
Not homogeneous

No special positions or directions in the Universe.
"The universe presents the same general aspect at every point"
Edward Arthur Milne
Also the Copernican principle : we are 'typical' observers.

THE 'PERFECT' VERSION WAS ABANDONED FOLLOWING THE DISCOVERY OF THE CMB IN 1964 AND THE REALIZATION THAT THE UNIVERSE *DOES* HAVE A BEGINNING ... BUT THE 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. …

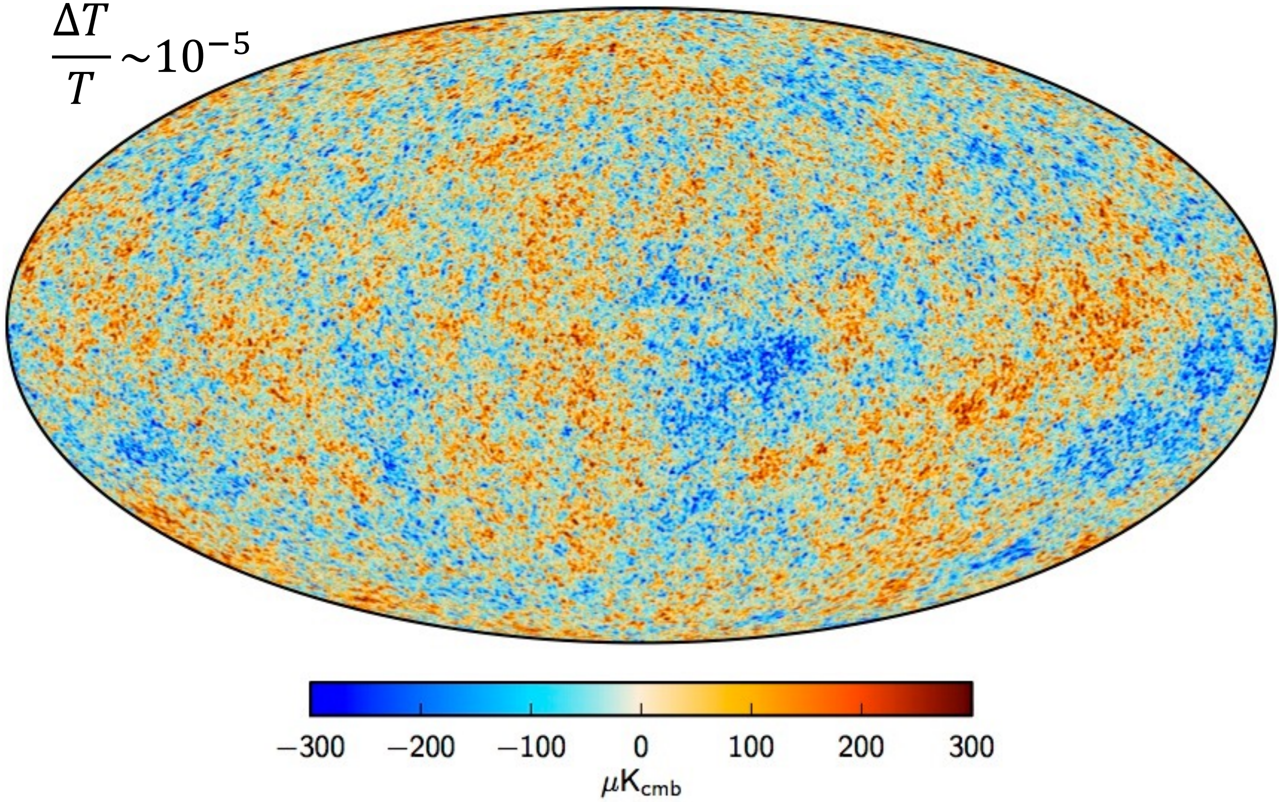
… If the data will not fit into this framework, we shall be able to conclude that either the Cosmological Principle or the Principle of Equivalence is wrong. Nothing could be more interesting.

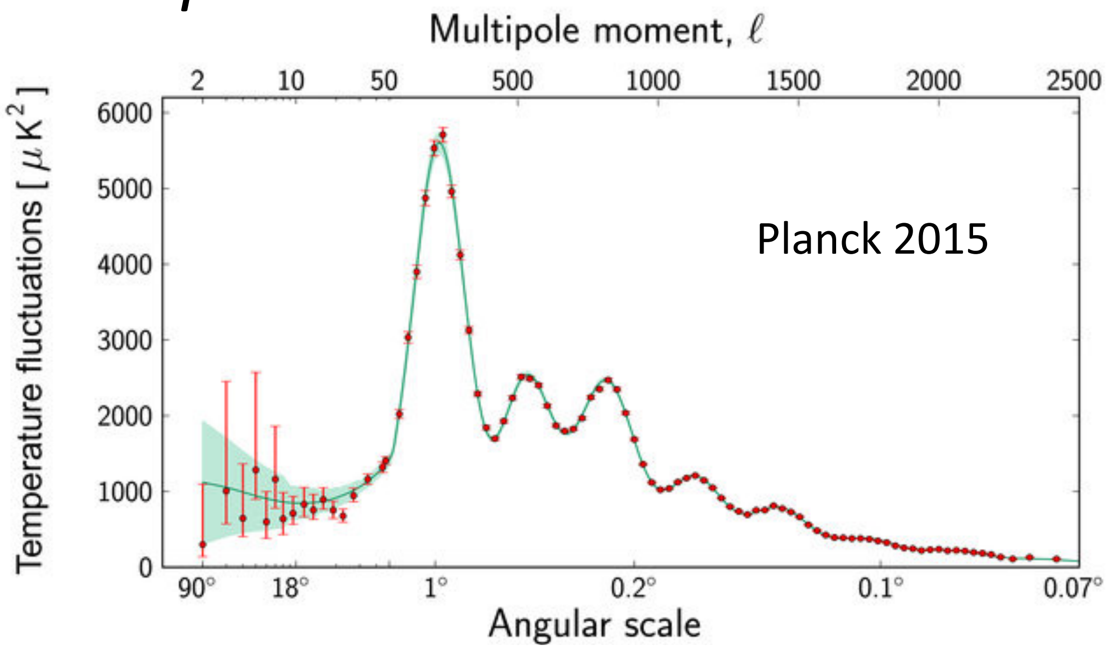
Steven Weinberg, *Gravitation and Cosmology* (1972)

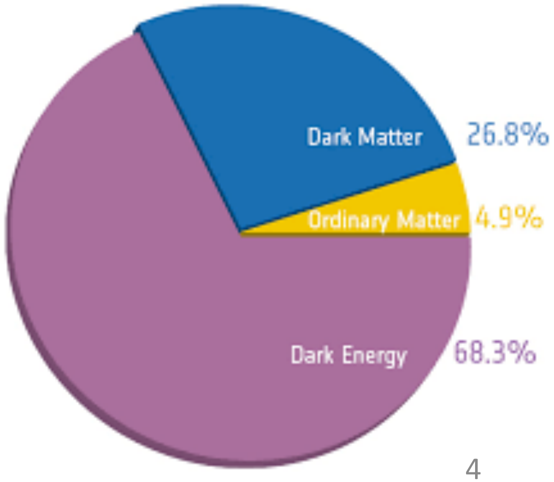
"Data from the Planck satellite show the Universe to be highly isotropic"

T = 2.725 K

$\frac{\Delta T}{T} \sim 10^{-5}$

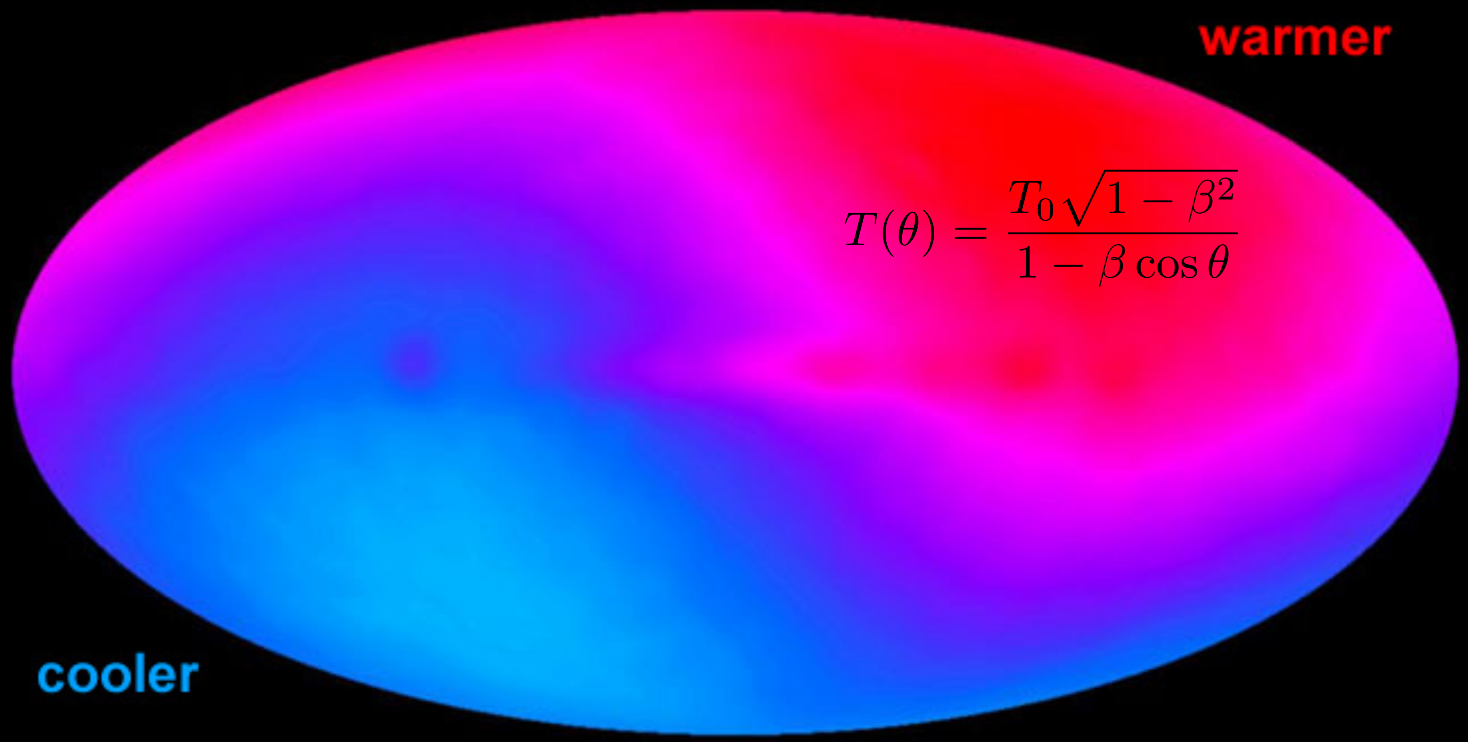






We observe a statistically isotropic Gaussian random field of small temperature fluctuations (fully quantified by the 2-point correlations ➛ angular power spectrum)

The CMB Dipole : Purely Kinematic?



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

COBE Experiment, 1996
Planck 2015

$$\frac{\Delta T}{T} \sim 10^{-3}$$

Net motion of the Solar System barycentre:
369 +/- 2 km/s w.r.t 'CMB rest frame' towards

R.A = 168.0, DEC = -7.0

Is this 'Purely Kinematic'?

What is the origin of this motion?

A moving observer - Kinematic Dipole

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

Ellis & Baldwin (1984)

Aberration

Rest frame

Moving frame

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

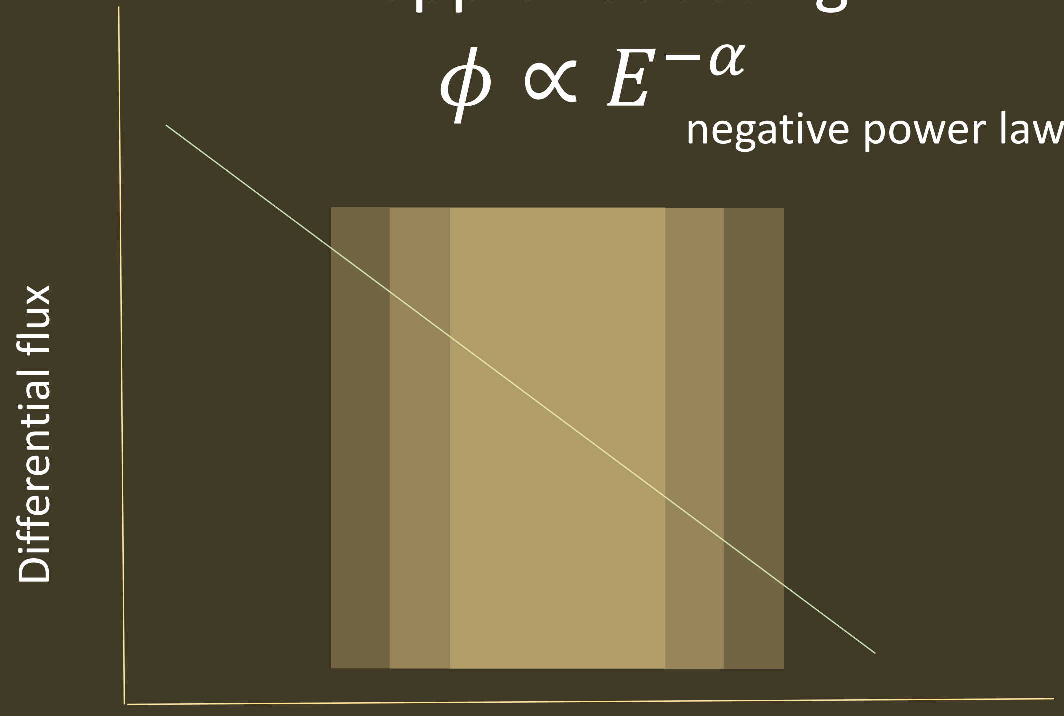
Observer, velocity v

\+

Doppler boosting

$$\phi \propto E^{-\alpha}$$

negative power law



Energy

Flux limited catalog -> more sources in direction of motion

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.

Needs a million sources to detect the CMB dipole velocity

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

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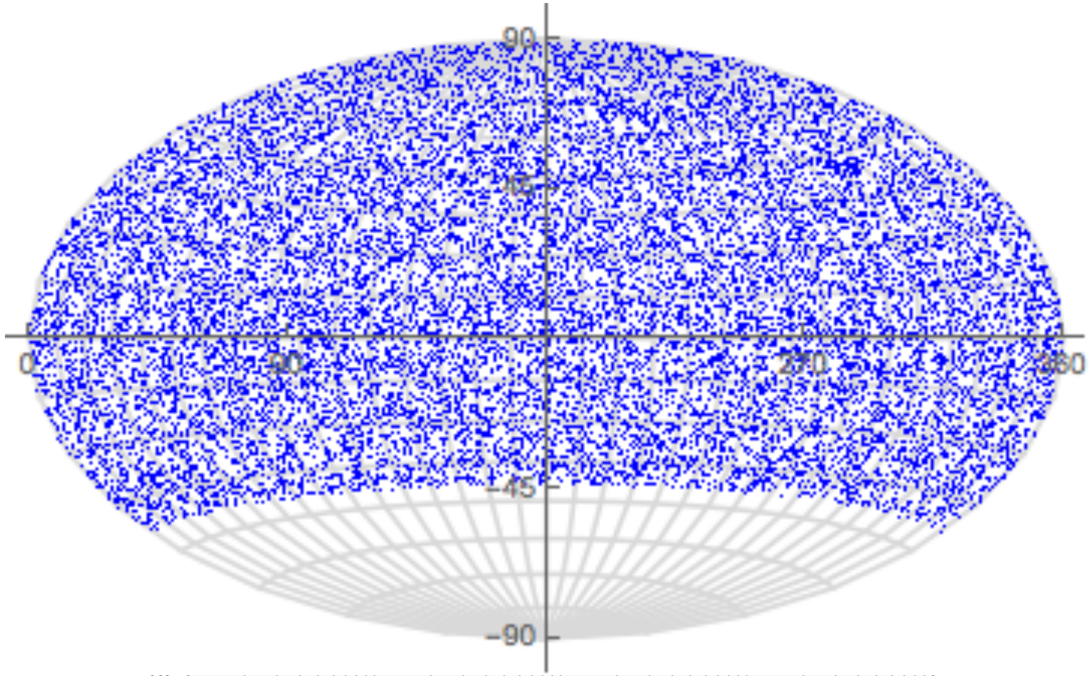
(c) the standard FRW Universe models.

Thus comparison of these standards of rest provides a powerful consistency test of our understanding of the Universe.

The situation anticipated by Ellis and Baldwin in 1984 now confronts us!

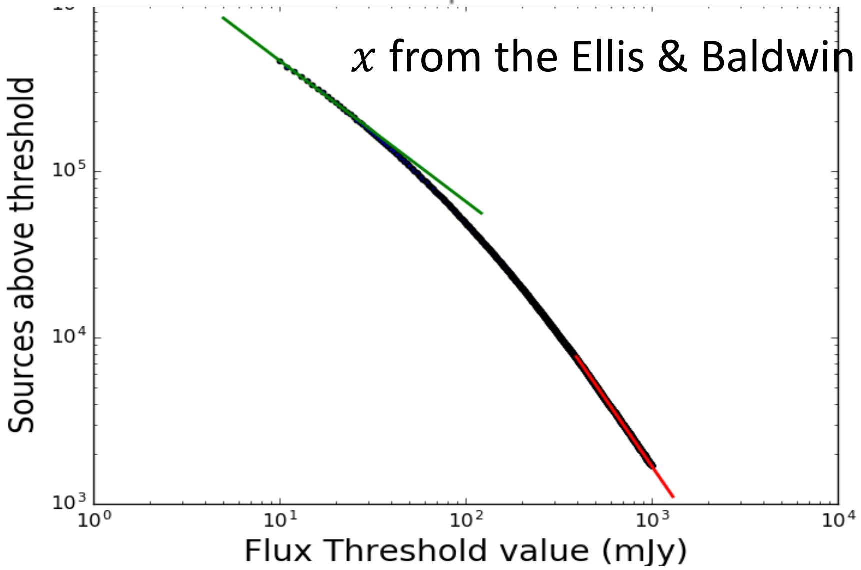
Ellis & Baldwin tests : The Cosmic Dipole Anomaly

The NRAO VLA Sky Survey (NVSS)



1.4 GHz survey of the Northern sky, by the National Radio Astronomy Observatory. Down to dec = -40.4°

1,773,488 sources above 2.5 mJy. But 'complete' with uniform sky exposure only above 10 mJy

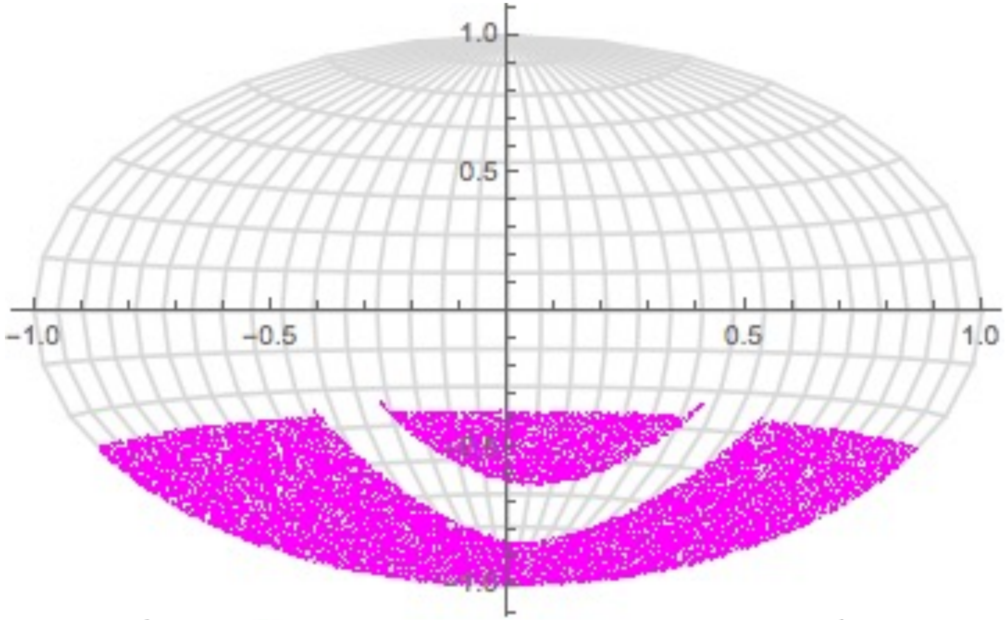


x from the Ellis & Baldwin expression

Phys. Rev. D, 78, 043519

First seen by Singal, A. K. 2011, ApJL, 742, L23,

Sydney University Molonglo Sky Survey (SUMSS)

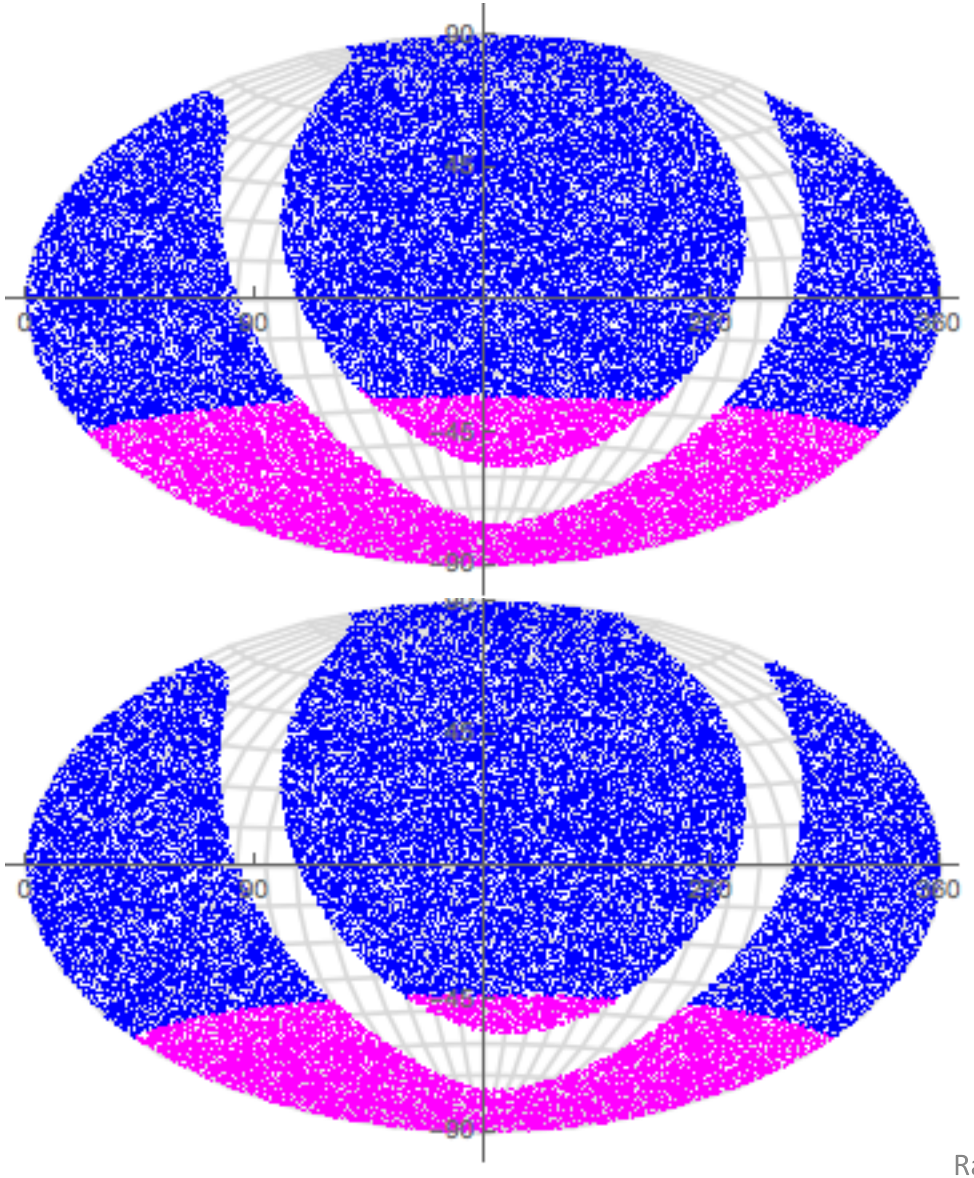


x from the Ellis & Baldwin formula

843 MHz survey of the Southern sky, by the Molonglo Observatory Synthesis telescope. Dec < -30.0^{o}

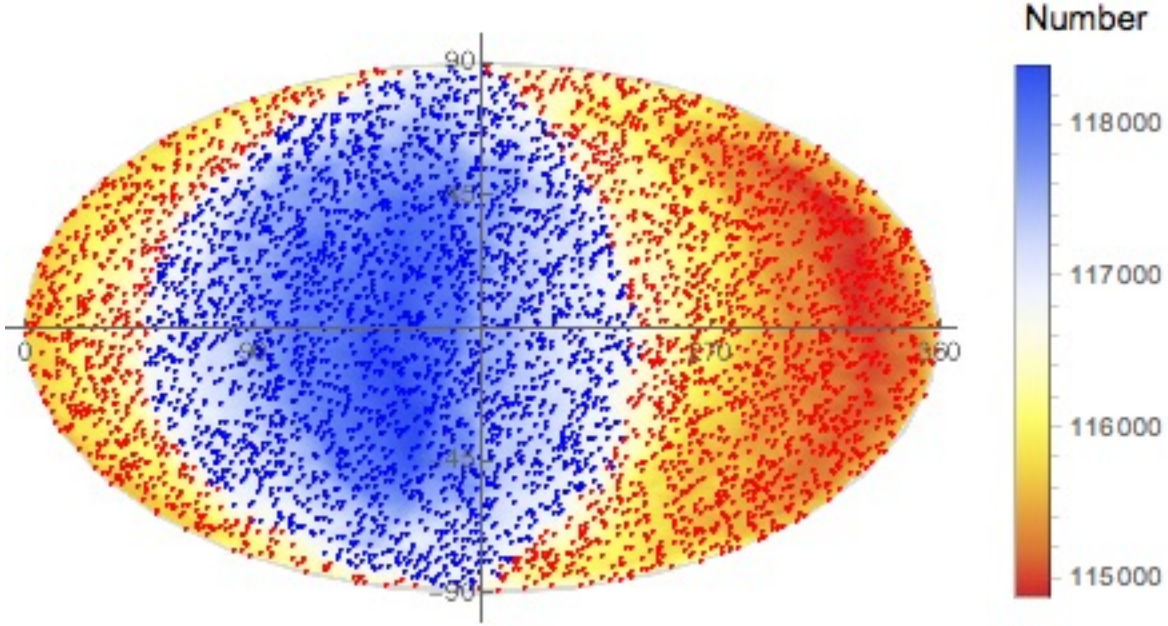
211050 radio sources. Similar sensitivity and resolution to NVSS

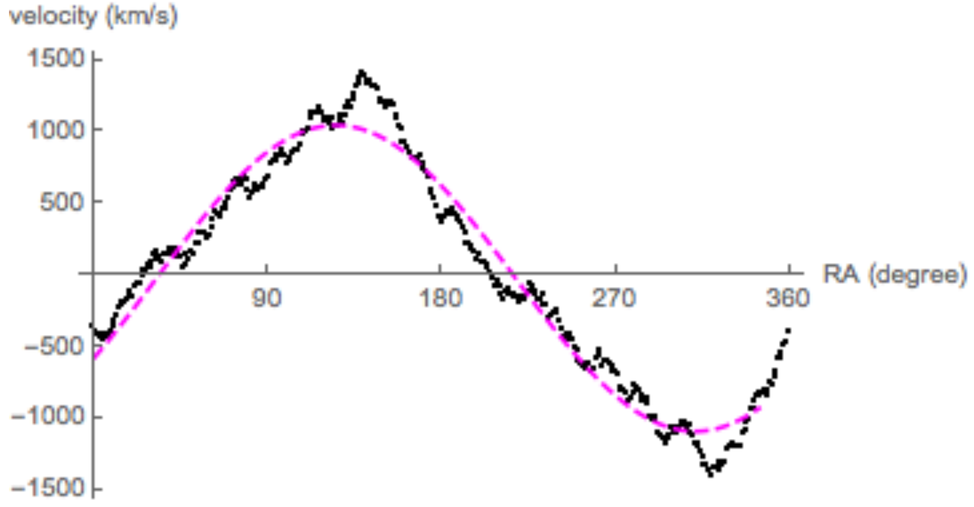
The NVSUMSS-Combined All Sky catalog



- Rescale SUMSS fluxes by $(843/1400)^{-0.75}$
- Remove Galactic Plane at +/-10 degree in NVSS
- Remove NVSS sources below and SUMSS sources above dec -30 (or -40)
- Apply common threshold flux cut on both samples
- z~1

Results





Velocity ~ 1355 $\pm$ 351 km/s, Dir within 10° of CMB dipole direction.

Statistical significance, ~2.81 Sigma, with the 3D linear estimator, constrained mainly by the catalogue size

Bengaly et al 2018 JCAP 1804 (2018) no.04, 031 find a 5.1 sigma excess in TGSS !

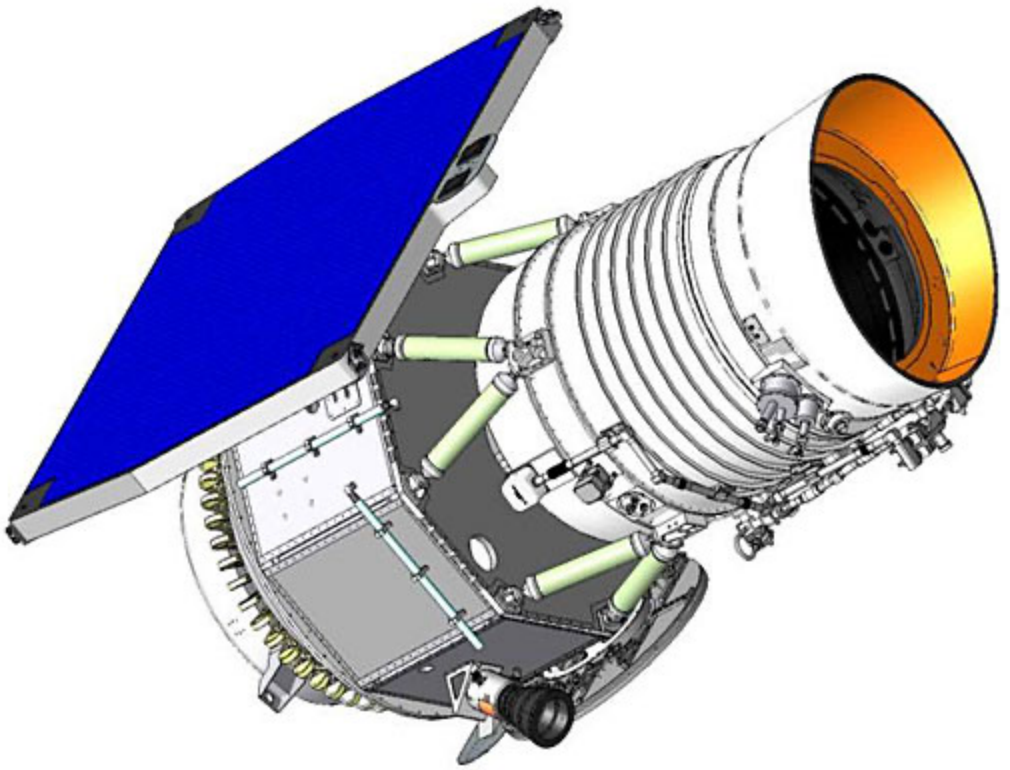
SKA phase 1 measurement ~10%

Bengaly (et al) 2018 MNRAS, 486, Issue 1 (2019) 1350-1357

"We conclude that for all analysed surveys, the observed Cosmic Radio Dipole amplitudes ***exceed the expectation, derived from the CMB dipole****."*

Siewert et al 2020, *Astron.Astrophys.* 653 (2021) A9

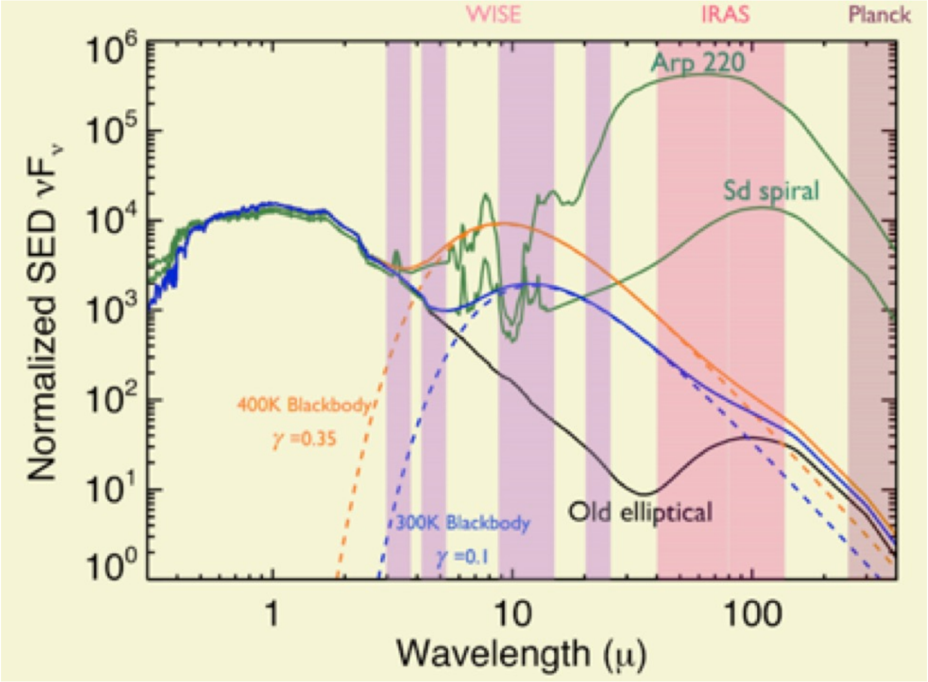
The Widefield Infrared Survey Explorer



All sky infrared survey over 10 months, in the bands 3.4, 4.6, 12 and 22 μm using a 40 cm diameter telescope

Generated a catalog of 746 million+ objects, most of which are stars.

Directionally unbiased survey strategy, arc second angular resolution, multi band photometry.



THE ASTROPHYSICAL JOURNAL LETTERS

OPEN ACCESS

A Test of the Cosmological Principle with Quasars

Nathan J. Secrest[1], Sebastian von Hausegger[2,3,4], Mohamed Rameez[5], Roya Mohayaee[3], Subir Sarkar[4], and Jacques Colin[3]

Published 2021 February 25 •

The Astrophysical Journal Letters, Volume 908, Number 2

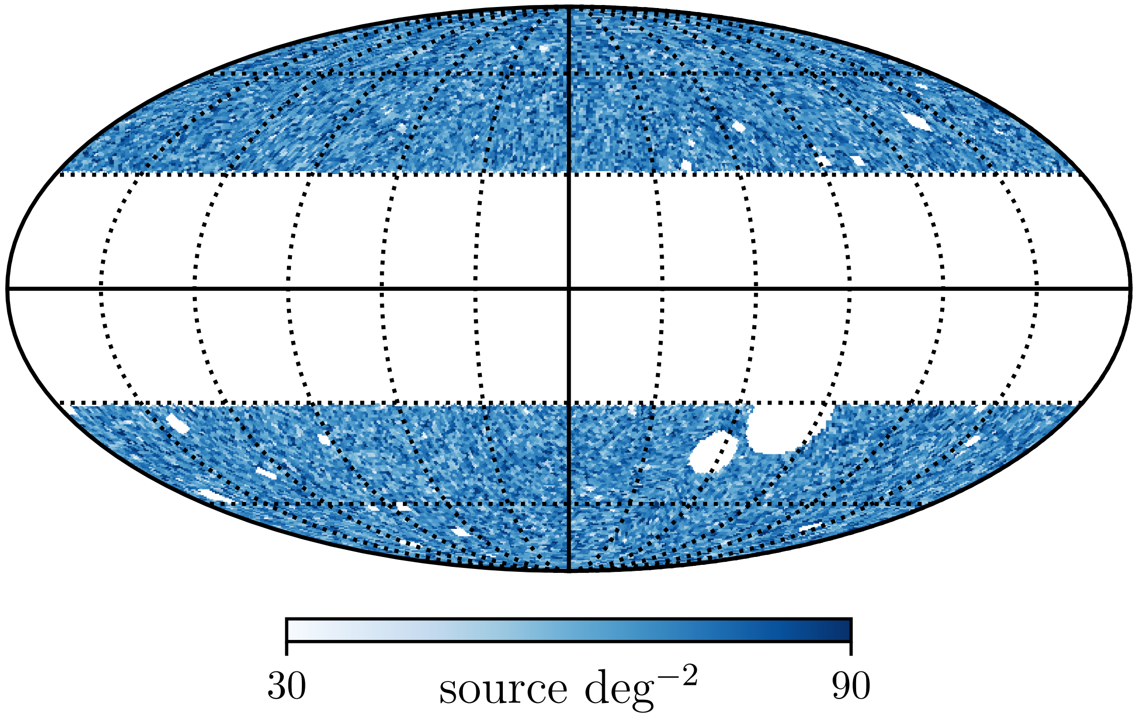
Citation Nathan J. Secrest *et al* 2021 *ApJL* **908** L51

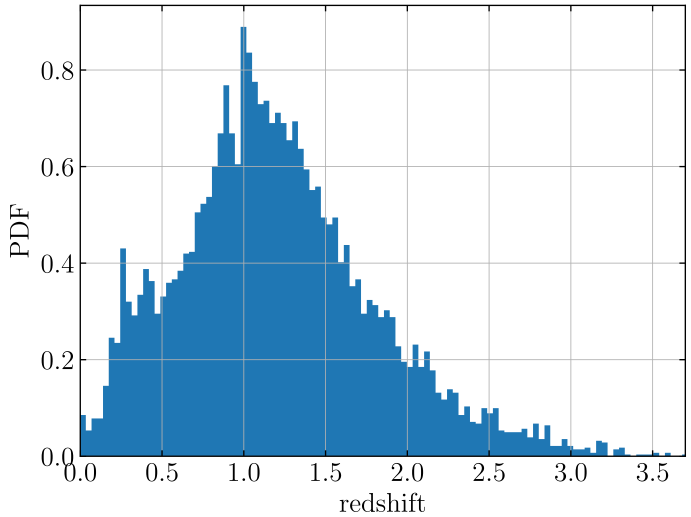
DOI 10.3847/2041-8213/abdd40

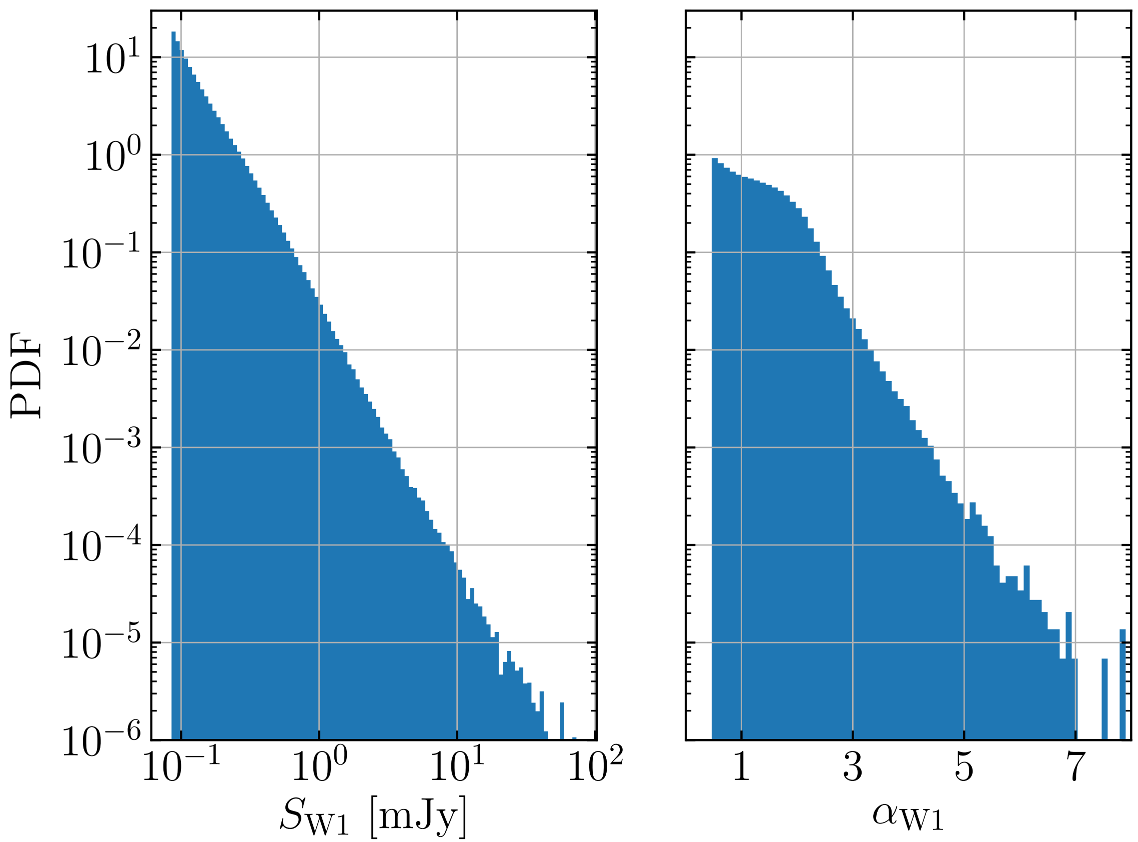
ABSTRACT

We study the large-scale anisotropy of the Universe by measuring the dipole in the angular distribution of a flux-limited, all-sky sample of 1.36 million quasars observed by the Wide-field Infrared Survey Explorer (WISE). This sample is derived from the new CatWISE2020 catalog, which contains deep photometric measurements at 3.4 and 4.6 μm from the cryogenic, post-cryogenic, and reactivation phases of the WISE mission. While the direction of the dipole in the quasar sky is similar to that of the cosmic microwave background (CMB), its amplitude is over twice as large as expected, rejecting the canonical, exclusively kinematic interpretation of the CMB dipole with a p-value of 5×10^{-7} (4.9σ for a normal distribution, one-sided), the highest significance achieved to date in such studies. Our results are in conflict with the cosmological principle, a foundational assumption of the concordance ΛCDM model.

CatWISE AGN 1355352 sources

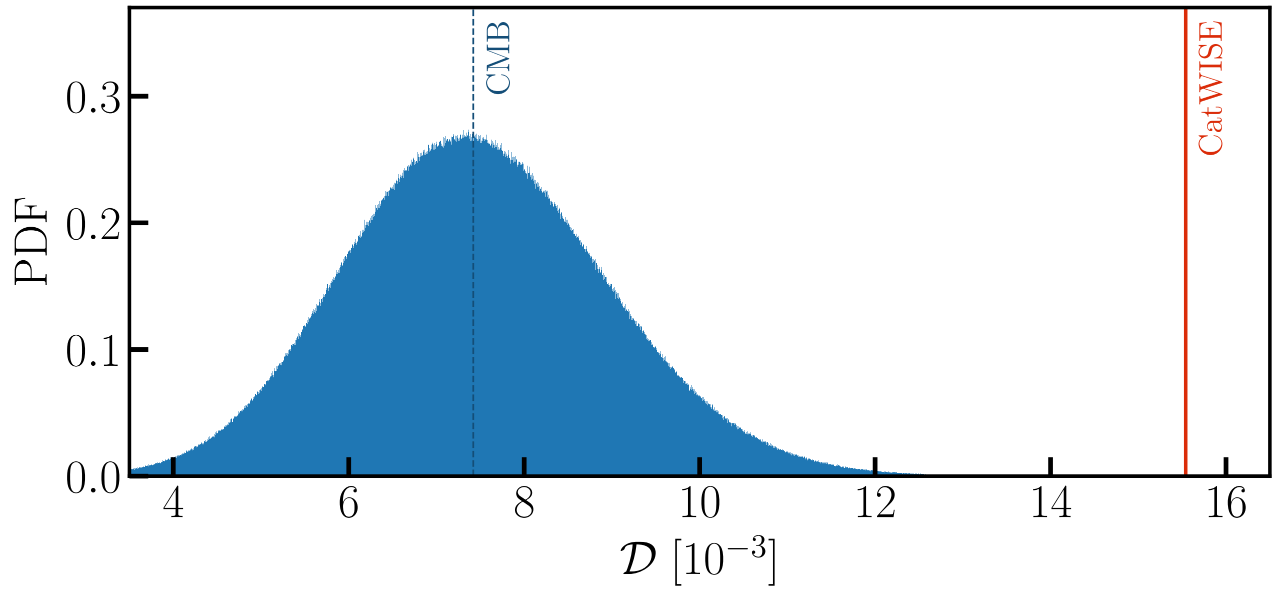


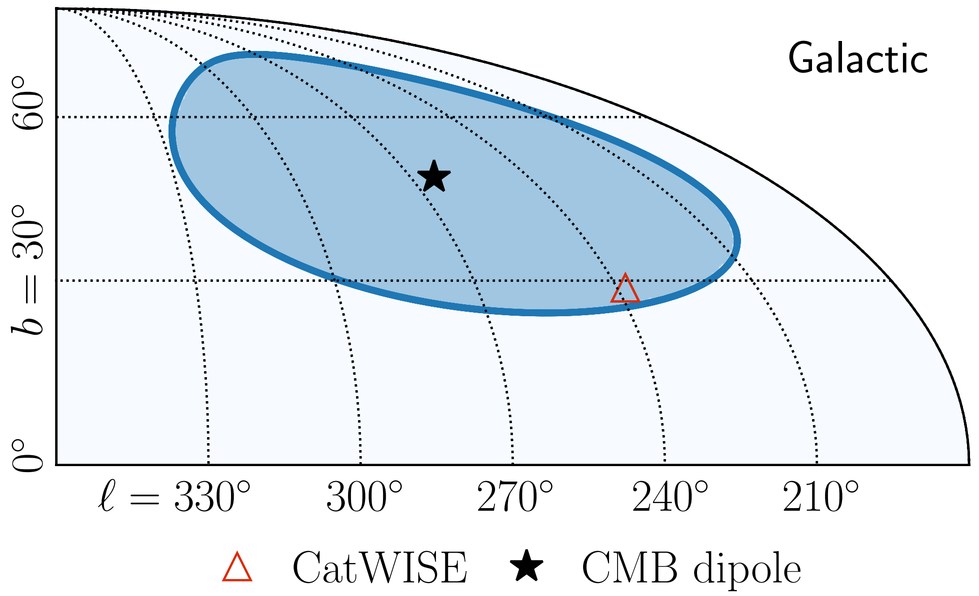




Astrophys.J.Lett. 908 (2021) 2, L51

Results

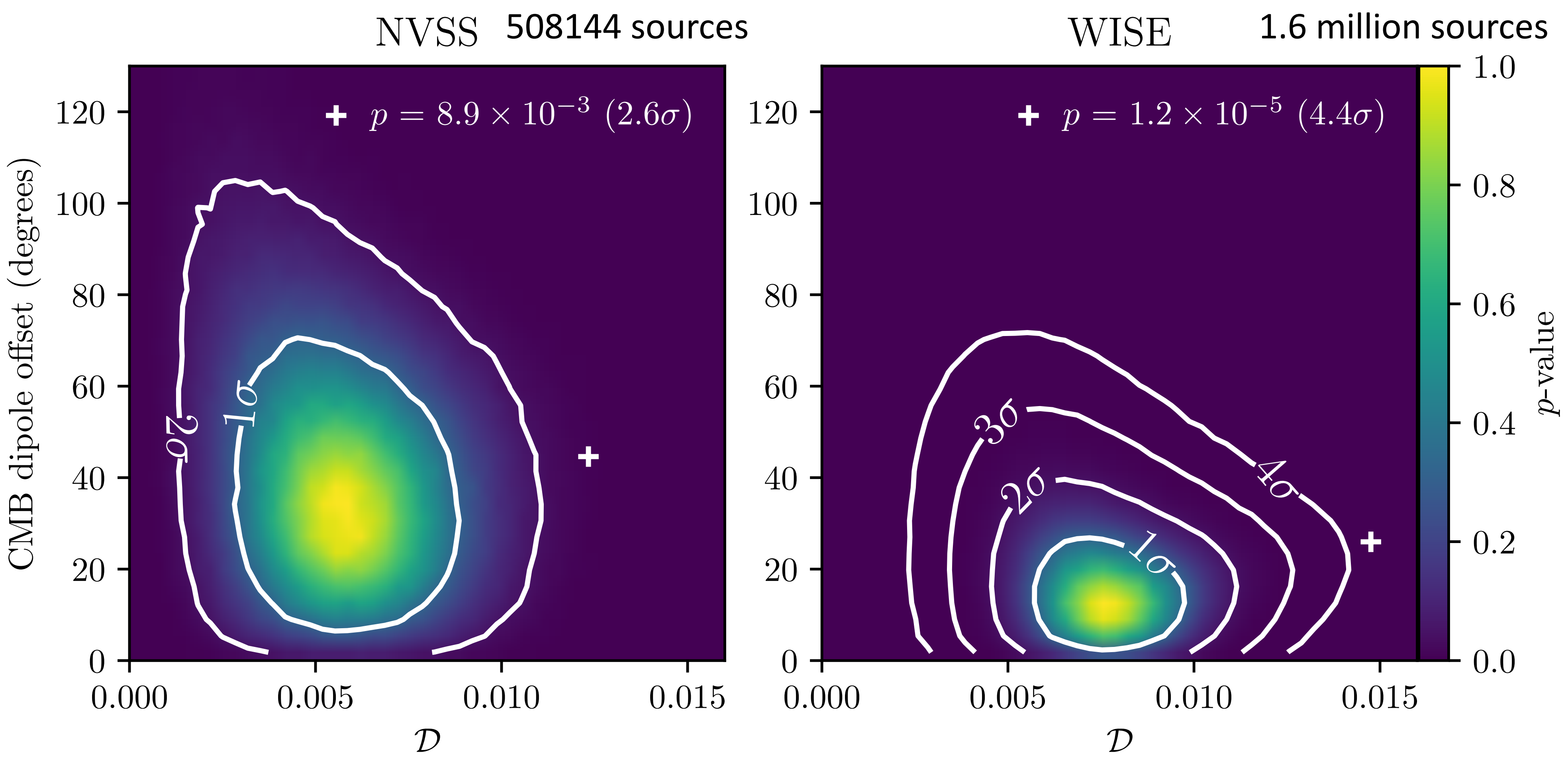




p = 5 $\times 10^{-7}$ (4.9 σ)

Obtained by scrambling the data itself,
frequentist null hypothesis testing,

Open Science https://zenodo.org/record/4448512



Conservative Sample size weighted Z-scores : 5.1 σ

Astrophys.J.Lett. 937 (2022) L31
https://zenodo.org/record/6784602

Also in a sample of z~0.2 galaxies
Mon.Not.Roy.Astron.Soc. 477 (2018) 2, 1772-1781 (backup slides)

Testing the Cosmological Principle with CatWISE Quasars: A Bayesian Analysis of the Number-Count Dipole

Lawrence Dam[1,2,★] Geraint F. Lewis[1†] & Brendon J. Brewer[3]

[1] *Sydney Institute for Astronomy, School of Physics, A28, The University of Sydney, NSW 2006, Australia*

[2] *Département de Physique Théorique and Center for Astroparticle Physics, Université de Genève, 24 quai Ernest-Ansermet, 1211 Genève 4, Switzerland*

[3] *Department of Statistics, The University of Auckland, Private Bag 92019, Auckland 1142, New Zealand*

Accepted XXX. Received YYY; in original form ZZZ

ABSTRACT

The Cosmological Principle, that the Universe is homogeneous and isotropic on sufficiently large scales, underpins the standard model of cosmology. However, 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 $5.7\,\sigma$. To compare these results with theoretical expectations, we sharpen the ΛCDM predictions for the probability distribution of the amplitude, taking into account a number of observational and theoretical systematics. In particular, we show that the presence of the galactic plane mask causes a considerable loss of dipole signal due to a leakage of power into higher multipoles, exacerbating the discrepancy in the amplitude. By contrast, we estimate using probabilistic arguments that the source evolution of quasars improves the discrepancy, but only mildly so. These results support the original findings of an anomalously large quasar dipole, independent of the statistical methodology used.

The response

Quanta magazine | Physics | Mathematics | Biology | Computer Science | Topics | Archive

COSMOLOGY

Cosmologists Parry Attacks on the Vaunted Cosmological Principle

27

A central pillar of cosmology — the universe is the same everywhere and in all directions — is surviving a storm of possible evidence against it.

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Health Space Physics Technology Environment Mind Humans Life Mathematics Chemistry Earth Society

Space

One of our most basic assumptions about the universe may be wrong

By Leah Crane

9 March 2021

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Health Space Physics Technology Environment Mind Humans Life Mathematics Chemistry Earth Society

Space

Controversial claim that the universe is skewed could upend cosmology

Our understanding of the universe is underpinned by the cosmological principle: the assumption that, on the grandest scales, it looks more or less the same in all directions. What if that's wrong?

By Thomas Lewton

Science THE WIRE

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THE SCIENCES

Is the Universe Different In Different Directions?

29/04/2021

Now known by the community as the “Cosmic Dipole Anomaly”

Dipole Cosmology: The Copernican Paradigm Beyond FLRW

Chethan KRISHNAN[a*], Ranjini MONDOL[a†], M. M. SHEIKH-JABBARI[b‡]

[a] Center for High Energy Physics,
Indian Institute of Science, Bangalore 560012, India
[b] School of Physics, Institute for Research in Fundamental Sciences (IPM),
P. O. Box 19395-5531, Tehran, Iran

SO(3) → U(1), tilted Bianchi V/VII_h - 4 Friedmann like equations

Large-scale geometry of the Universe

Yassir Awwad[♠] and Tomislav Prokopec[◇]

[◇] Institute for Theoretical Physics, Spinoza Institute & EMMEΦ
Utrecht University, Princetonplein 5, 3584 CC Utrecht, The Netherlands

Thursten Perelman theorem -> anisotropic Thursten geometries should be considered on par with Friedmann geometry

Spatially Homogeneous Universes with Late-Time Anisotropy

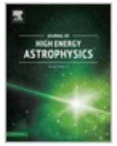
Andrei Constantin,[1,*] Thomas R. Harvey,[1,†] Sebastian von Hausegger,[2,‡] and Andre Lukas[1,§]
[1] *Rudolf Peierls Centre for Theoretical Physics, University of Oxford, Parks Road, Oxford, UK*
[2] *Astrophysics, University of Oxford, Denys Wilkinson Building, Keble Road, Oxford, UK*

QCD axion dark matter and the cosmic dipole anomaly

Chengcheng Han[1,*]
[1] *School of Physics, Sun Yat-Sen University, Guangzhou 510275, China*
(Dated: November 29, 2022)

Highlighted by PDG 2022 as one of the principal anomalies in Cosmology.

ELSEVIER
Journal of High Energy Astrophysics
Volume 34, June 2022, Pages 49-211



Review

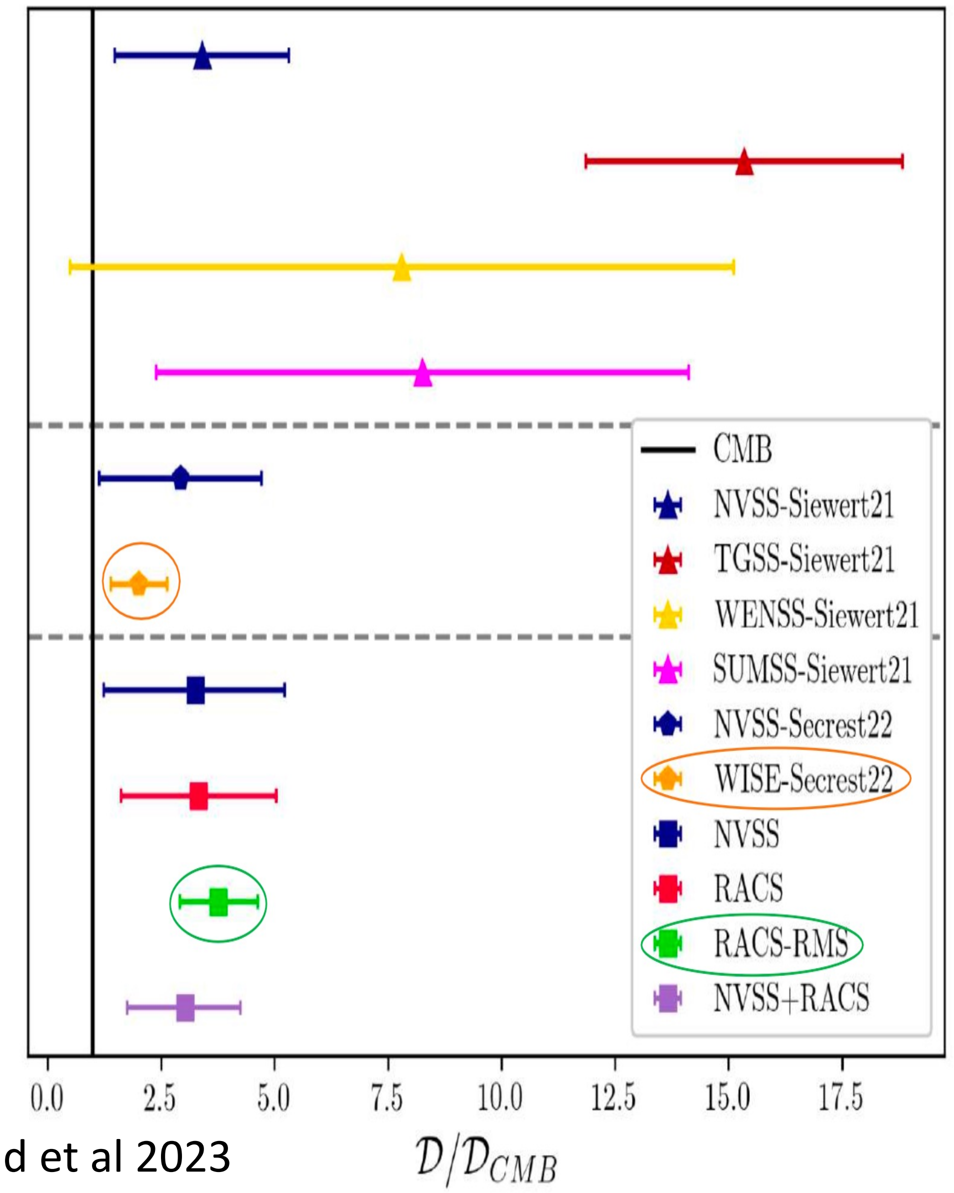
Cosmology intertwined: A review of the particle physics, astrophysics, and cosmology associated with the cosmological tensions and anomalies

Elcio Abdalla [a], Guillermo Franco Abellán [b], Amin Aboubrahim [c], Adriano Agnello [d], Özgür Akarsu [e], Yashar Akrami [f g h i], George Alestas [j], Daniel Aloni [k], Luca Amendola [l], Luis A. Anchordoqui [m n o], Richard I. Anderson [p], Nikki Arendse [q], Marika Asgari [r s], Mario Ballardini [t u v w], Vernon Barger [x], Spyros Basilakos [y z], Ronaldo C. Batista [aa], Elia S. Battistelli [ab ac], Richard Battye [ad], Micol Benetti [ae af]… Miguel Zumalacárregui [gw]

Cosmic Dipole Anomaly, right beside the Hubble tension
Peebles 2022, 2024

"Standard cosmology would then need a drastic revision, with implications for DM."
Cirelli, Strumia and Zupan 2024

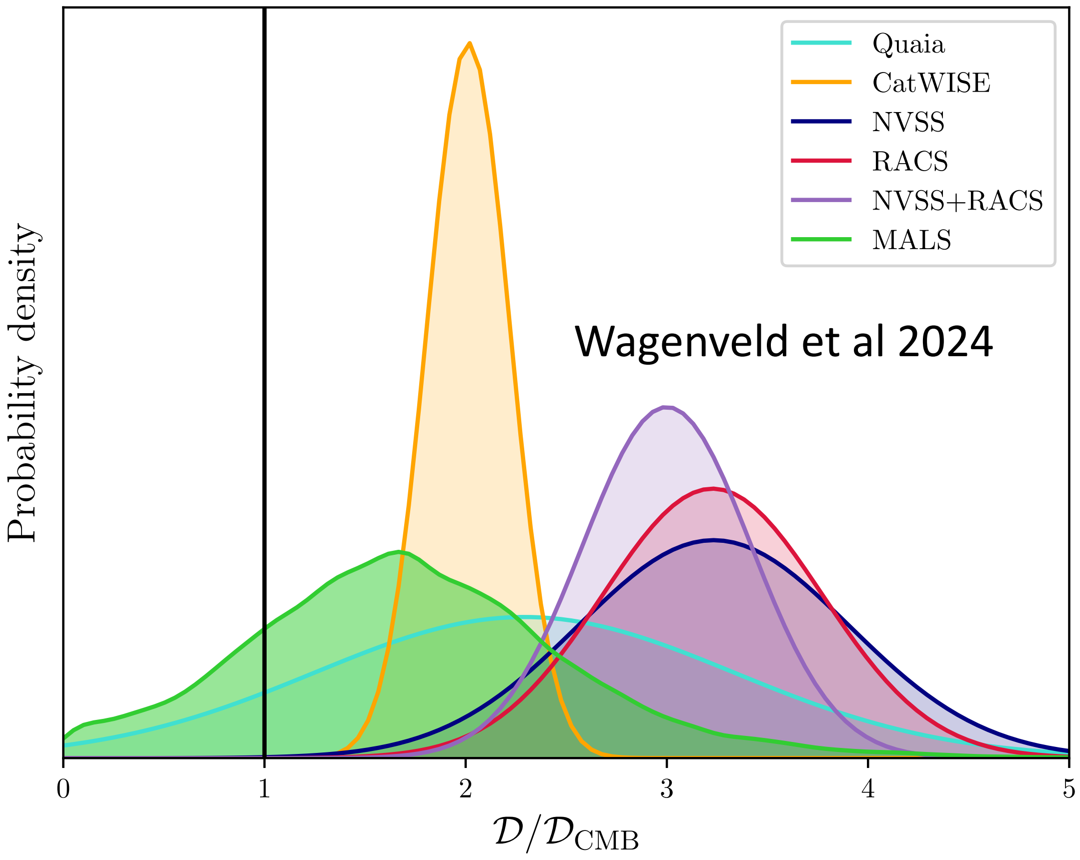
The cosmic radio dipole: Bayesian estimators on new and old radio surveys



Wagenveld et al 2023

Wagenveld, Klöckner, Schwarz, A&A 675:A72,2023

Dipole amplitudes with 3σ uncertainties compared to the amplitude expected from the CMB



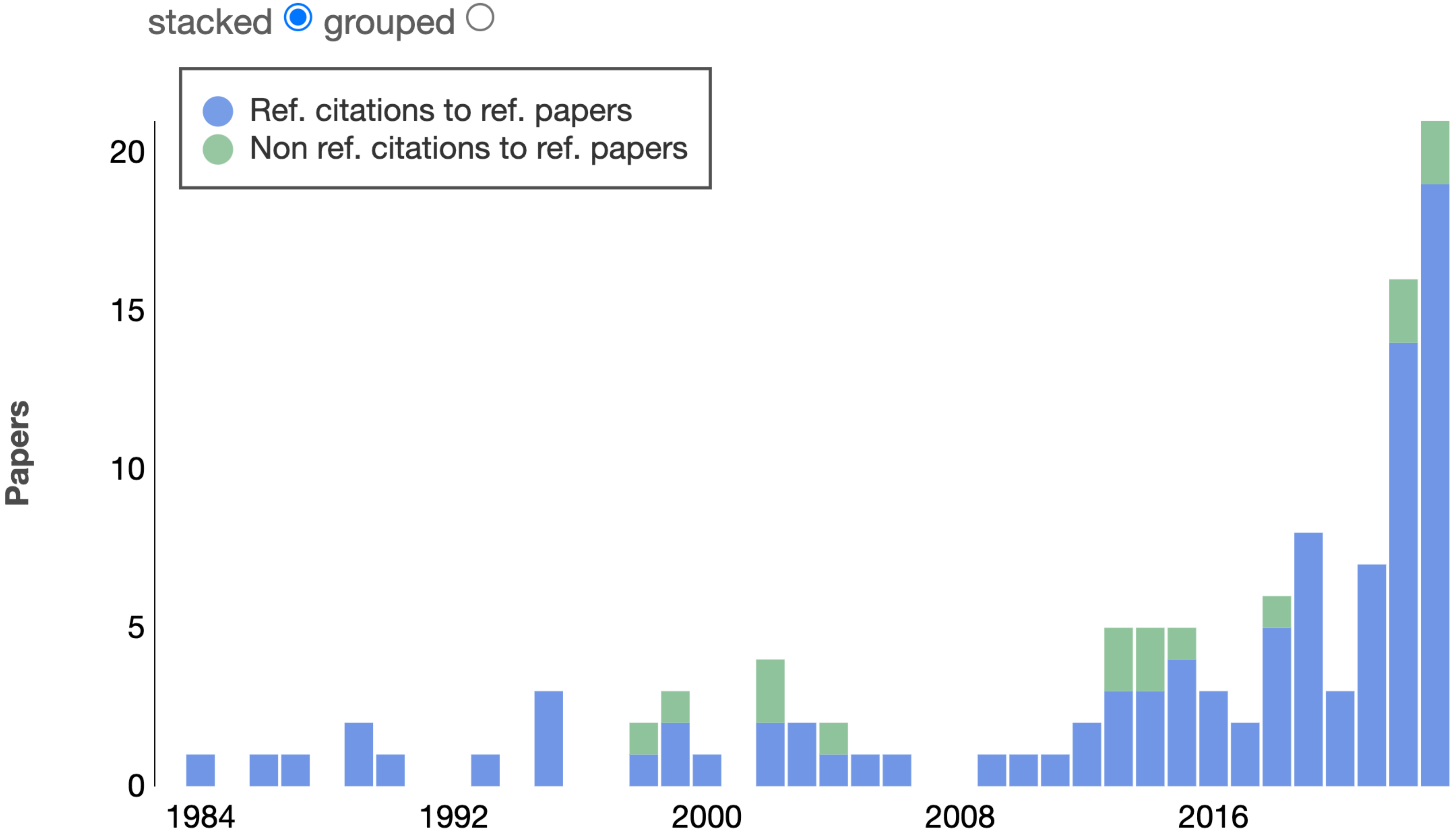
Wagenveld et al 2024

10+ papers that claim consistency with the kinematic expectation in **other** datasts.

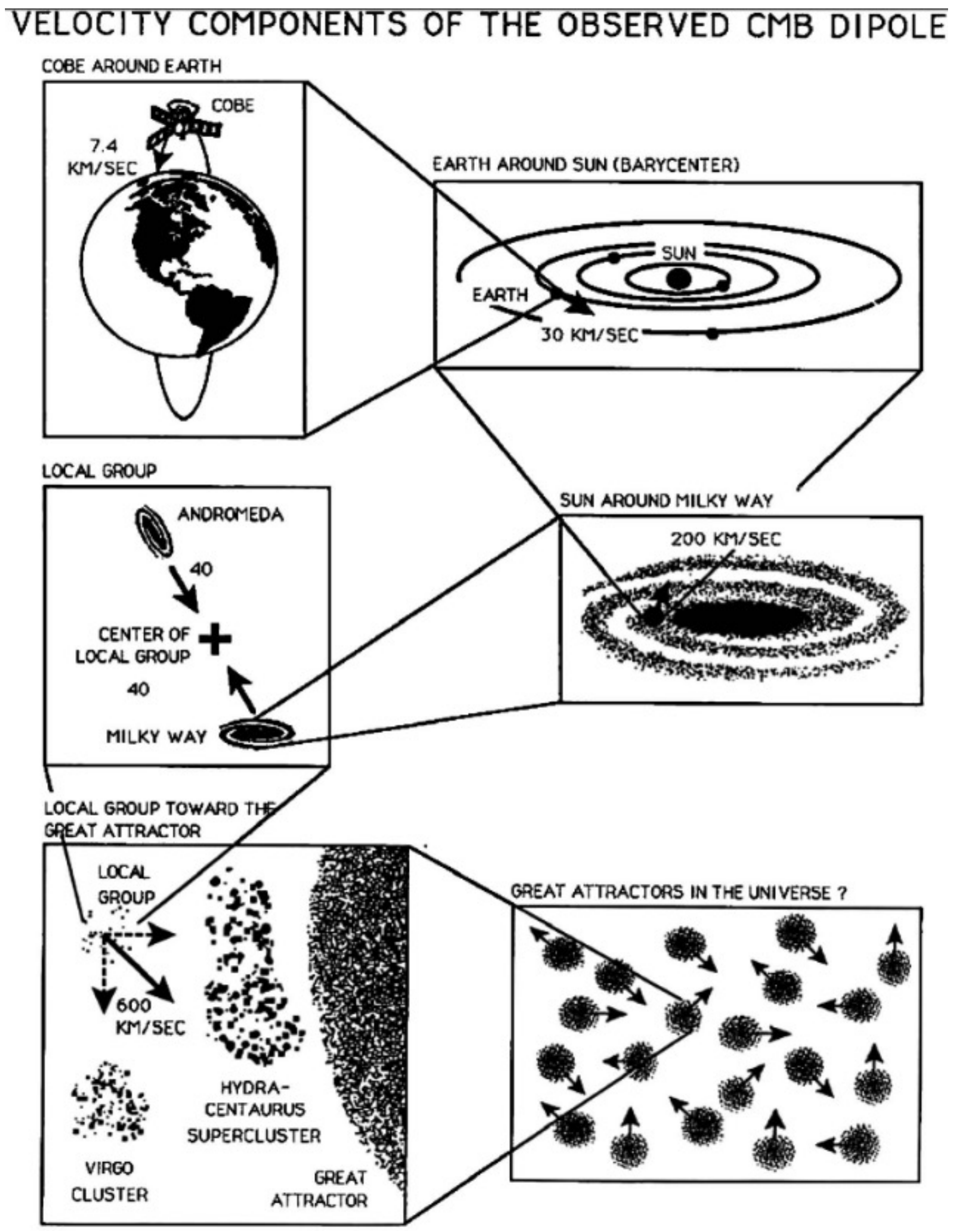
Watch out for upcoming RevModPhys review.

SKA, Euclid, SphereX

Citations to Ellis & Baldwin 1984

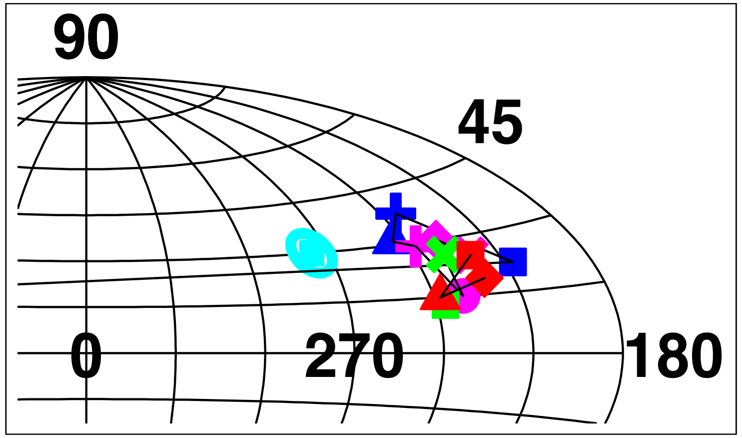


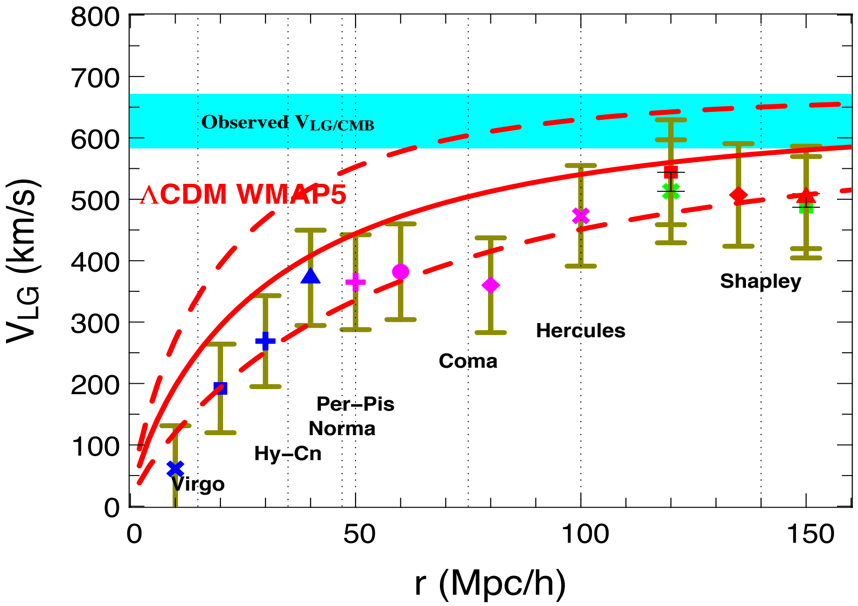
Bulk flows and a tilted Universe in SNe 1a



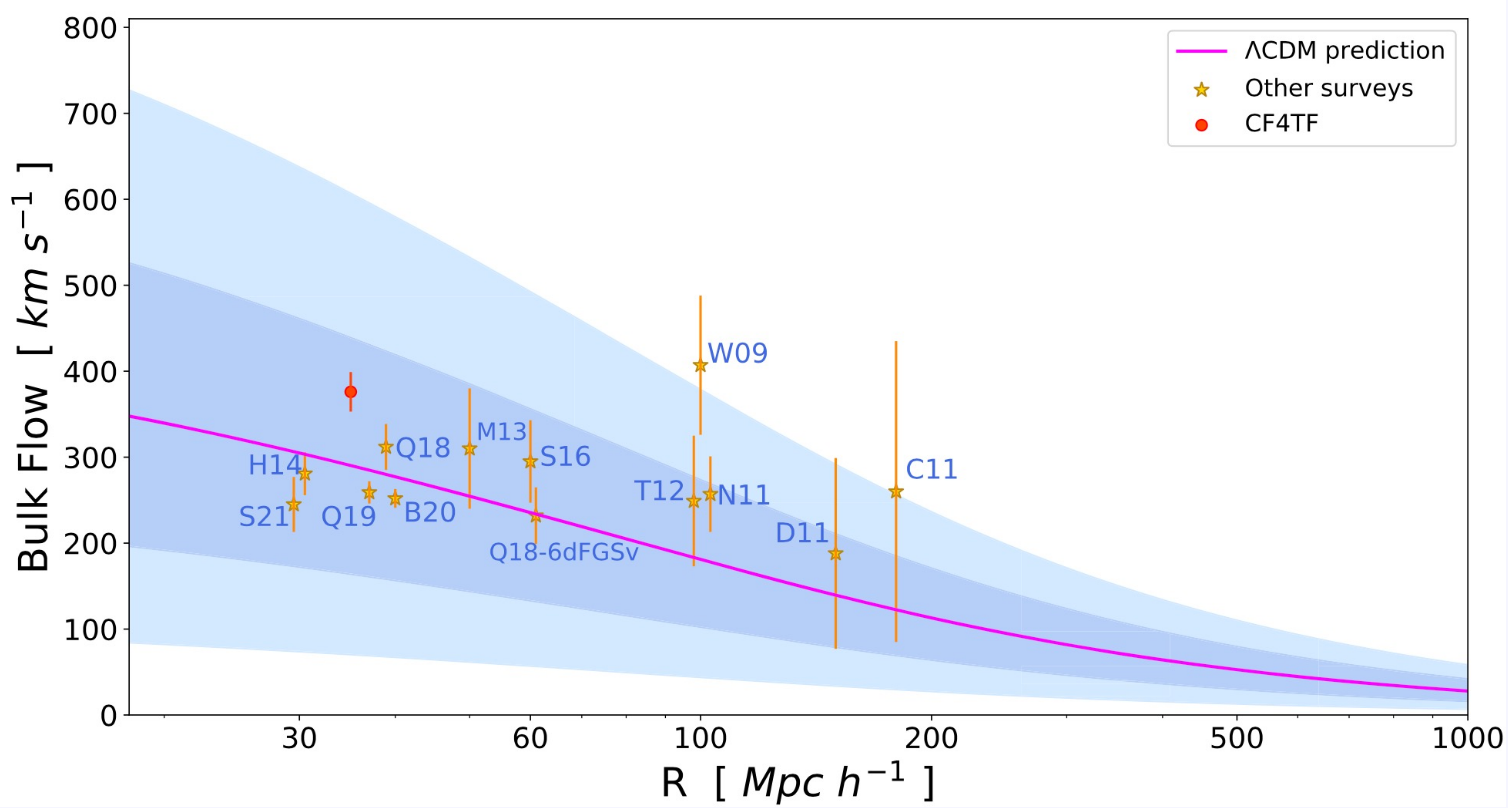
George Smoot, Nobel Lecture, 8 Dec 2006

Where is the cosmic 'rest frame'?





CONVERGENCE TO THE 'CMB FRAME' IS NOT SEEN EVEN OUT TO ~200/h MPC



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.

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

G. Lavaux, R.Brent Tully, R. Mohayaee, S. Colombi

• *Astrophys.J.* 709 (2010) 483-498

Letter to the Editor

Gravity in the Local Universe: density and velocity fields using CosmicFlows-4

H.M. Courtois[⋆1], A. Dupuy[2], D. Guinet[1], G. Baulieu[1], and F. Ruppin[1]

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[2] Korea Institute for Advanced Study, 85, Hoegi-ro, Dongdaemun-gu, Seoul 02455, Republic of Korea

Received A&A Oct 31, 2022 - AA/2022/45331; Accepted date

ABSTRACT

This article publicly releases three-dimensional reconstructions of the local Universe gravitational field below z=0.8 that were computed using the full catalogue CosmicFlows-4 of 56,000 galaxy distances and its sub-sample of 1,008 type Ia supernovae distances. The article also provides some first CF4 measurements of the growth rate of structure using the pairwise correlation of peculiar velocities $f\sigma_8 = 0.44(\pm 0.01)$ and of the bulk flow in the Local Universe of 200 ± 88 kms^1 at distance 300 h^{-1}_{100} Mpc.

Key words. Cosmology: large-scale structure of Universe

Analyzing the Large-Scale Bulk Flow using CosmicFlows4: Increasing Tension with the Standard Cosmological Model

Richard Watkins[†,1], Trey Allen[†], Collin James Bradford[†], Albert Ramon Jr.[†], Alexandra Walker[†], Hume A. Feldman[⋆,2], Rachel Cionitti[⋆], Yara Al-Shorman Ehsan Kourkchi[††], & R. Brent Tully[††]

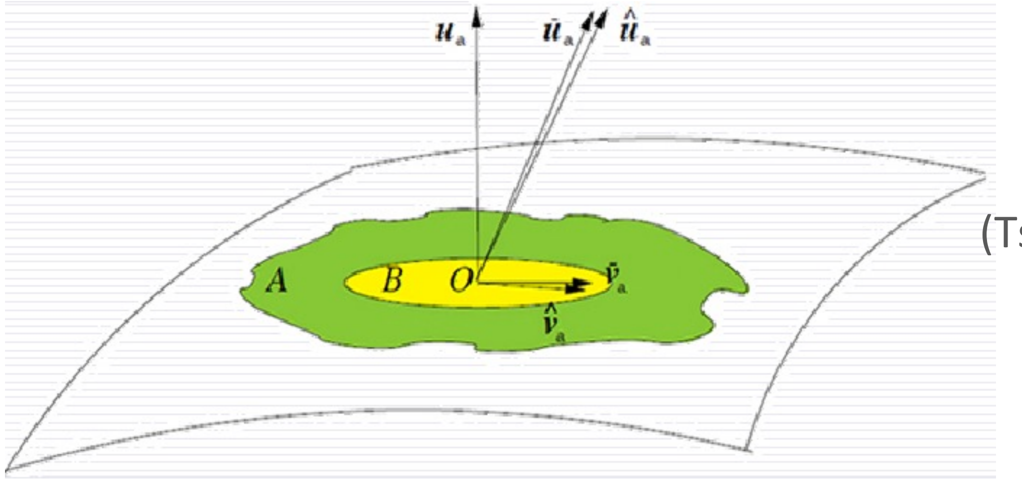
[†] *Department of Physics, Willamette University, Salem, OR 97301, USA.*
[⋆] *Department of Physics & Astronomy, University of Kansas, Lawrence, KS 66045, USA.*
[††] *Institute for Astronomy, University of Hawaii, Honolulu, HI 96822, USA.*
emails: [1]rwatkins@willamette.edu; [2]feldman@ku.edu

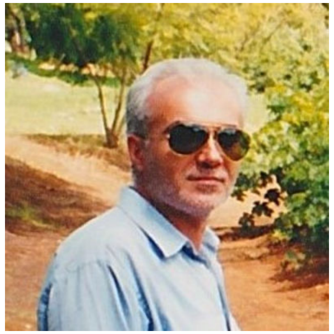
7 February 2023

ABSTRACT

We present an estimate of the bulk flow in a volume of radii $150-200h^{-1}$Mpc using the minimum variance (MV) method with data from the *CosmicFlows-4* (CF4) catalog. The addition of new data in the CF4 has resulted in an increase in the estimate of the bulk flow in a sphere of radius $150h^{-1}$Mpc relative to the *CosmicFlows-3* (CF3). This bulk flow has less than a 0.03% chance of occurring in the Standard Cosmological Model (ΛCDM) with cosmic microwave background derived parameters. Given that the CF4 is deeper than the CF3, we were able to use the CF4 to accurately estimate the bulk flow on scales of $200h^{-1}$Mpc (equivalent to 266 Mpc for Hubble constant $H_o = 75$ km/s/Mpc) for the first time. This bulk flow is in even greater tension with the Standard Model, having less than 0.003% probability of occurring. To estimate the bulk flow accurately, we introduce a novel method to calculate distances and velocities from distance moduli that is unbiased and accurate at all distances. Our results are completely independent of the value of H_o.

The tilted Friedmann Universe





If we are inside a large local 'bulk flow'.

(Tsagas 2010, 2011, 2012; Tsagas & Kadiltzoglou 2015, Tsagas 2019, 2021)

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 accelerating or decelerating)

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 observer 'measures' *negative* deceleration parameter in one direction of the sky - – i.e. towards the CMB dipole

This implies that **observers** experiencing locally accelerated expansion, as a result of their own drift motion, may also find that the acceleration is maximised in one direction and minimised in the opposite. We argue that, typically, such a dipole anisotropy should be relatively small and the axis should probably **lie fairly close to the one seen in the spectrum of the Cosmic Microwave Background.**

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Astronomy & Astrophysics

Letter to the Editor

Evidence for anisotropy of cosmic acceleration★

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Using the SDSS-II/SNLS-3 Joint Lightcurve Analysis (JLA) compilation of 740 SNe

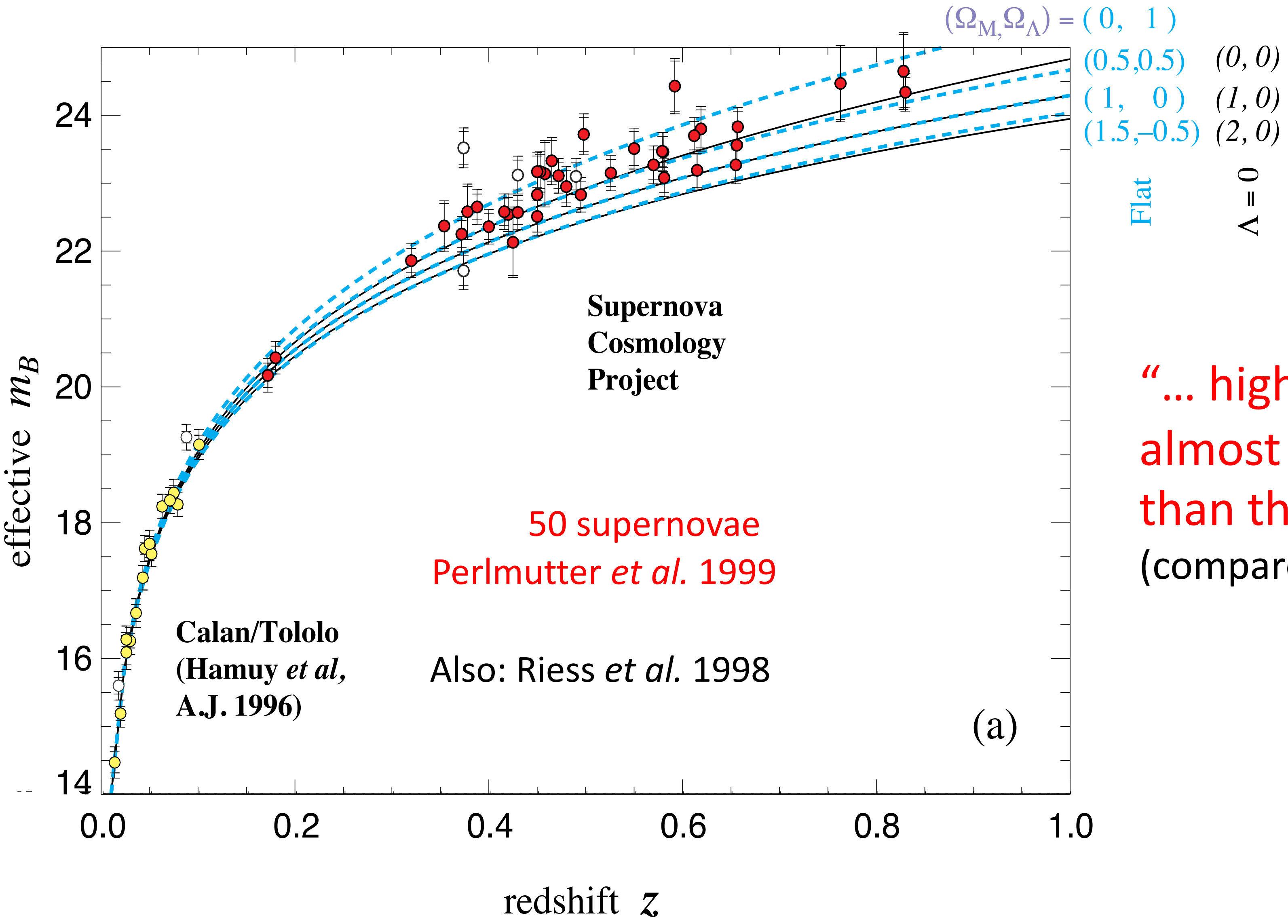
Ensuing debate

Rubin & Heitlauf 2019
Rahman et al 2021

ABSTRACT

Observations reveal a "bulk flow" in the local Universe which is faster and extends to much larger scales than are expected around a typical observer in the standard ΛCDM cosmology. This is expected to result in a scale-dependent dipolar modulation of the acceleration of the expansion rate inferred from observations of objects within the bulk flow. From a maximum-likelihood analysis of the Joint Light-curve Analysis catalogue of Type Ia supernovae, we find that the deceleration parameter, in addition to a small monopole, indeed has a much bigger dipole component aligned with the cosmic microwave background dipole, which falls exponentially with redshift z: $q_0 = q_m + \boldsymbol{q}_d.\hat{n}\exp(-z/S)$. The best fit to data yields $q_d = -8.03$ and $S = 0.0262$ ($\Rightarrow d \sim 100\,\mathrm{Mpc}$), rejecting isotropy ($q_d = 0$) with 3.9σ statistical significance, while $q_m = -0.157$ and consistent with no acceleration ($q_m = 0$) at 1.4σ. Thus the cosmic acceleration deduced from supernovae may be an artefact of our being non-Copernican observers, rather than evidence for a dominant component of "dark energy" in the Universe.

The discovery of dark energy



"… high redshift supernovae appear almost 0.15 mag (~15% in flux) fainter than the low redshift supernovae"

(compared to expectation for $\Lambda = 0$ universe)

SDSS-II/SNLS 3 Joint Lightcurve Analysis, 2014

(SALT 2 For making ‘stretch’ and ’colour’ corrections to the observed lightcurves)

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

B-band

SALT 2 parameters

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

Name	z_{cmb}	$m_B^\star$	X_1	C	$M_{stellar}$
03D1ar	0.002	23.941 ± 0.033	−0.945 ± 0.209	0.266 ± 0.035	10.1 ± 0.5
03D1au	0.503	23.002 ± 0.088	1.273 ± 0.150	−0.012 ± 0.030	9.5 ± 0.1
03D1aw	0.581	23.574 ± 0.090	0.974 ± 0.274	−0.025 ± 0.037	9.2 ± 0.1
03D1ax	0.495	22.960 ± 0.088	−0.729 ± 0.102	−0.100 ± 0.030	11.6 ± 0.1
03D1bp	0.346	22.398 ± 0.087	−1.155 ± 0.113	−0.041 ± 0.027	10.8 ± 0.1
03D1co	0.678	24.078 ± 0.098	0.619 ± 0.404	−0.039 ± 0.067	8.6 ± 0.3
03D1dt	0.611	23.285 ± 0.093	−1.162 ± 1.641	−0.095 ± 0.050	9.7 ± 0.1
03D1ew	0.866	24.354 ± 0.106	0.376 ± 0.348	−0.063 ± 0.068	8.5 ± 0.8
03D1fc	0.331	21.861 ± 0.086	0.650 ± 0.119	−0.018 ± 0.024	10.4 ± 0.0
03D1fq	0.799	24.510 ± 0.102	−1.057 ± 0.407	−0.056 ± 0.065	10.7 ± 0.1
03D3aw	0.450	22.667 ± 0.092	0.810 ± 0.232	−0.086 ± 0.038	10.7 ± 0.0
03D3ay	0.371	22.273 ± 0.091	0.570 ± 0.198	−0.054 ± 0.033	10.2 ± 0.1
03D3ba	0.292	21.961 ± 0.093	0.761 ± 0.173	0.116 ± 0.035	10.2 ± 0.1
03D3bl	0.356	22.927 ± 0.087	0.056 ± 0.193	0.205 ± 0.030	10.8 ± 0.1

There may well be other variables that the magnitude correlates with …

The ingredients of the fit

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

$$= 25 + 5\log_{10}\frac{d_L}{Mpc}$$

$$-c^2 d\tau^2 = = c^2 dt^2 + a(t)^2\, d\Sigma^2$$

Exact

$$d_L = (1+z)\frac{d_H}{\sqrt{\Omega_k}}\sinh\left(\sqrt{\Omega_k}\int_0^z \frac{H_0 dz'}{H(z')}\right),$$

$$d_H = c/H_0, \quad H_0 \equiv 100h \text{ km s}^{-1}\text{Mpc}^{-1},$$

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

- $H = \frac{\dot a}{a}$
- $q \stackrel{\text{def}}{=} -\frac{\ddot a a}{\dot a^2}$ (defined with a minus to be positive for a decelerating universe)
- $j = \frac{\dddot a}{aH^3}$

Kinematic

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

Visser 2004

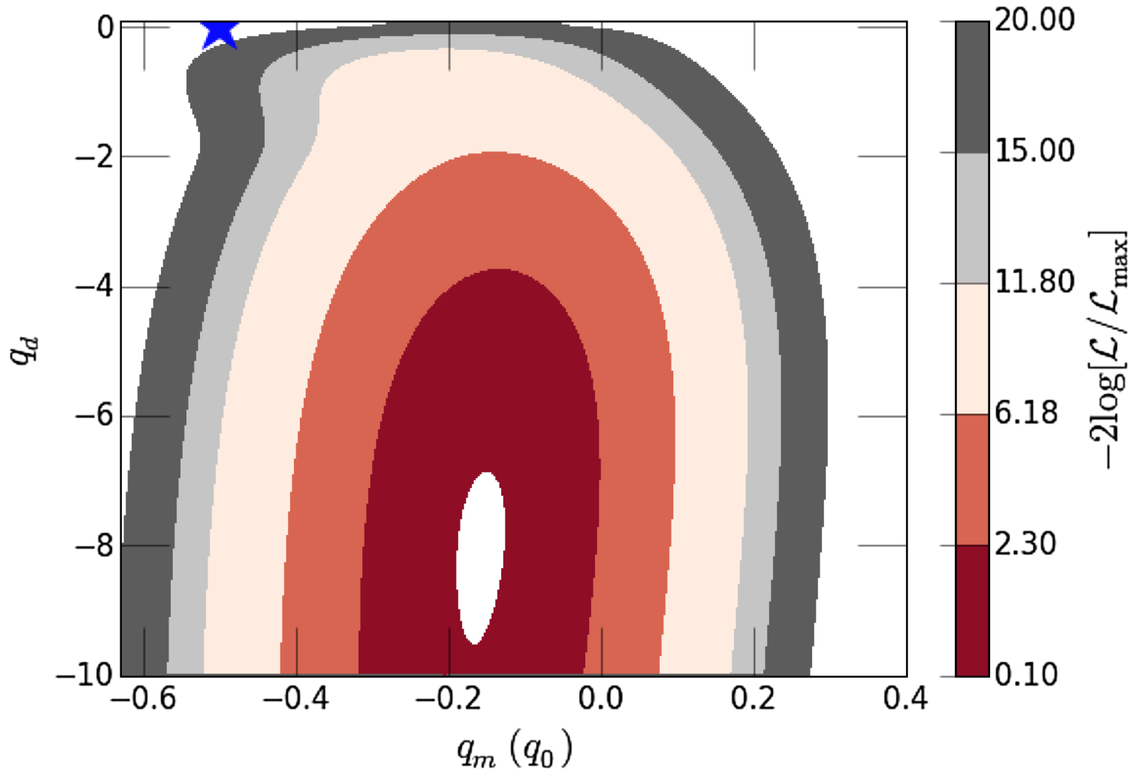
$$q = \frac{\Omega_M}{2} - \Omega_\Lambda \text{ (in } \Lambda CDM)$$

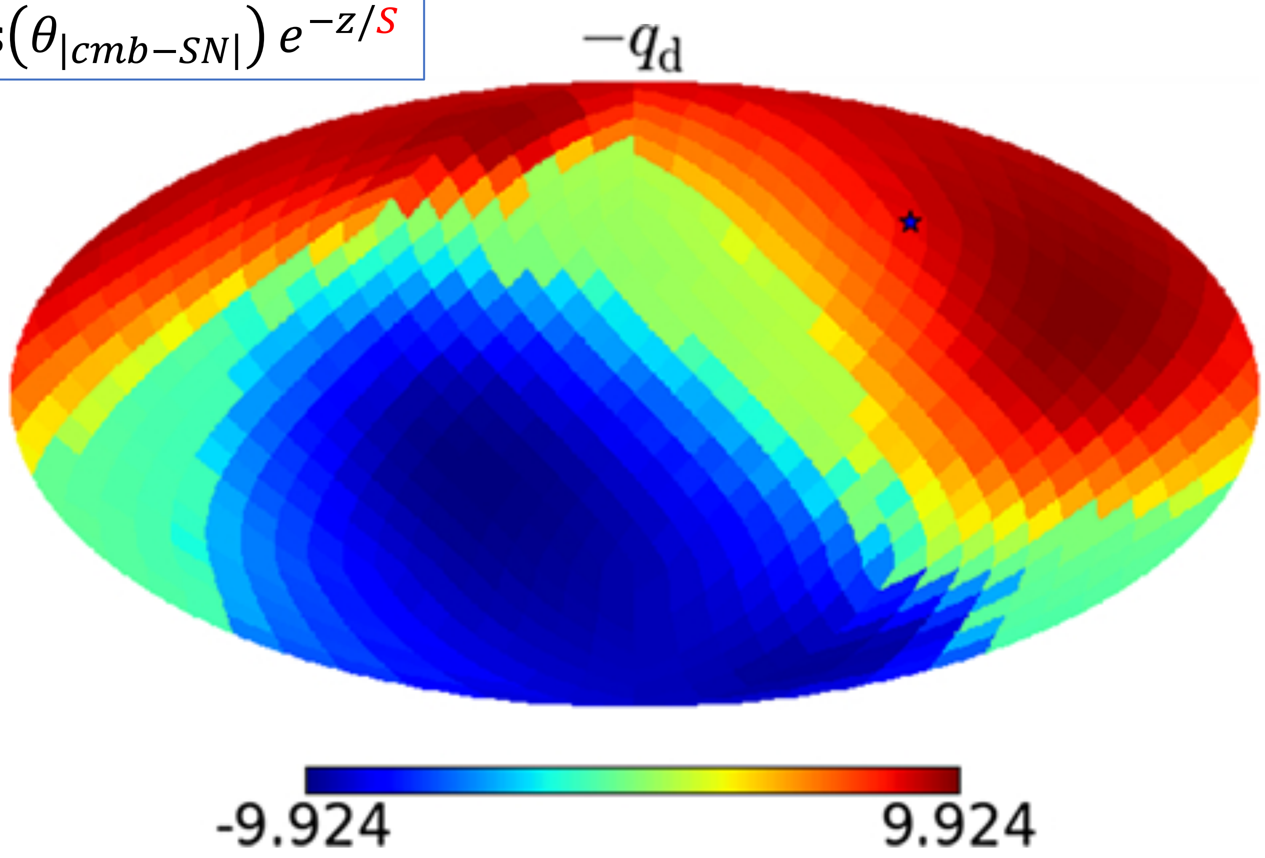
Concordance cosmology is given by

$$\Omega_M \sim 0.3, \Omega_\Lambda \sim 0.7$$
$$\Omega_k \sim 0$$
$$H \sim 70\ km\ s^{-1} Mpc^{-1}$$

Scale dependent Dipole in the deceleration parameter

Tilt: $q_0 \rightarrow q_m + q_d \cos(\theta_{|cmb-SN|})\, e^{-z/S}$





The dipolar component of acceleration is larger than the monopole, and dominates out to $z \sim 0.1$. Statistically significant @ 3.9 σ

$$q_d >> q_m$$

The statistical significance of the Universe accelerating isotropically is $<1.4\sigma$!

Cosmic acceleration, (and dark energy) may simply be an artefact of our being located inside a 'bulk flow'
… in accordance with the prediction of Tsagas (2011)

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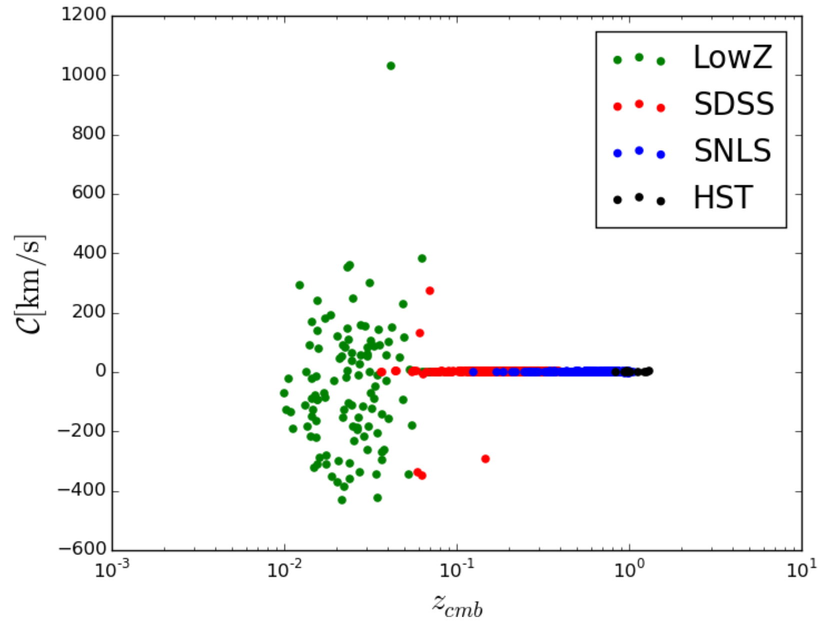
Contentious Issue : We used the heliocentric redshifts.

```
#name zcmb zhel dz mb dmb x1 dx1 color dcolor
03D1au 0.503084 0.504300 0 23.001698 0.088031
03D1aw 0.580724 0.582000 0 23.573937 0.090132
03D1ax 0.494795 0.496000 0 22.960139 0.088110
03D1bp 0.345928 0.347000 0 22.398137 0.087263
03D1co 0.677662 0.679000 0 24.078115 0.098356
03D1dt 0.610712 0.612000 0 23.285241 0.092877
03D1ew 0.866494 0.868000 0 24.353678 0.106037
03D1fc 0.330932 0.332000 0 21.861412 0.086437
03D1fg 0.798566 0.800000 0 24.510389 0.101777
```

A choice described as 'shocking' by Rubin & Heitlauf 2019

$$C = \left[(1 + z_{hel}) - (1 + z_{cmb})\left(1 + z_{pec}^{hel}\right)\right] \times c$$



$$1 + z_{hel} = \left(1 + z_{pec}^{hel}\right) \times (1 + \bar{z}) \times \left(1 + z_{pec}^{SN}\right)$$

$z_{hel} \rightarrow measured$

$z_{cmb}\ (\bar{z}) \rightarrow inferred\ using\ a\ flow\ model$

Davis *et al.* Astrophys.J. 741 (2011) 67
Ellis & Stoeger (1987)
"The fitting problem in cosmology"

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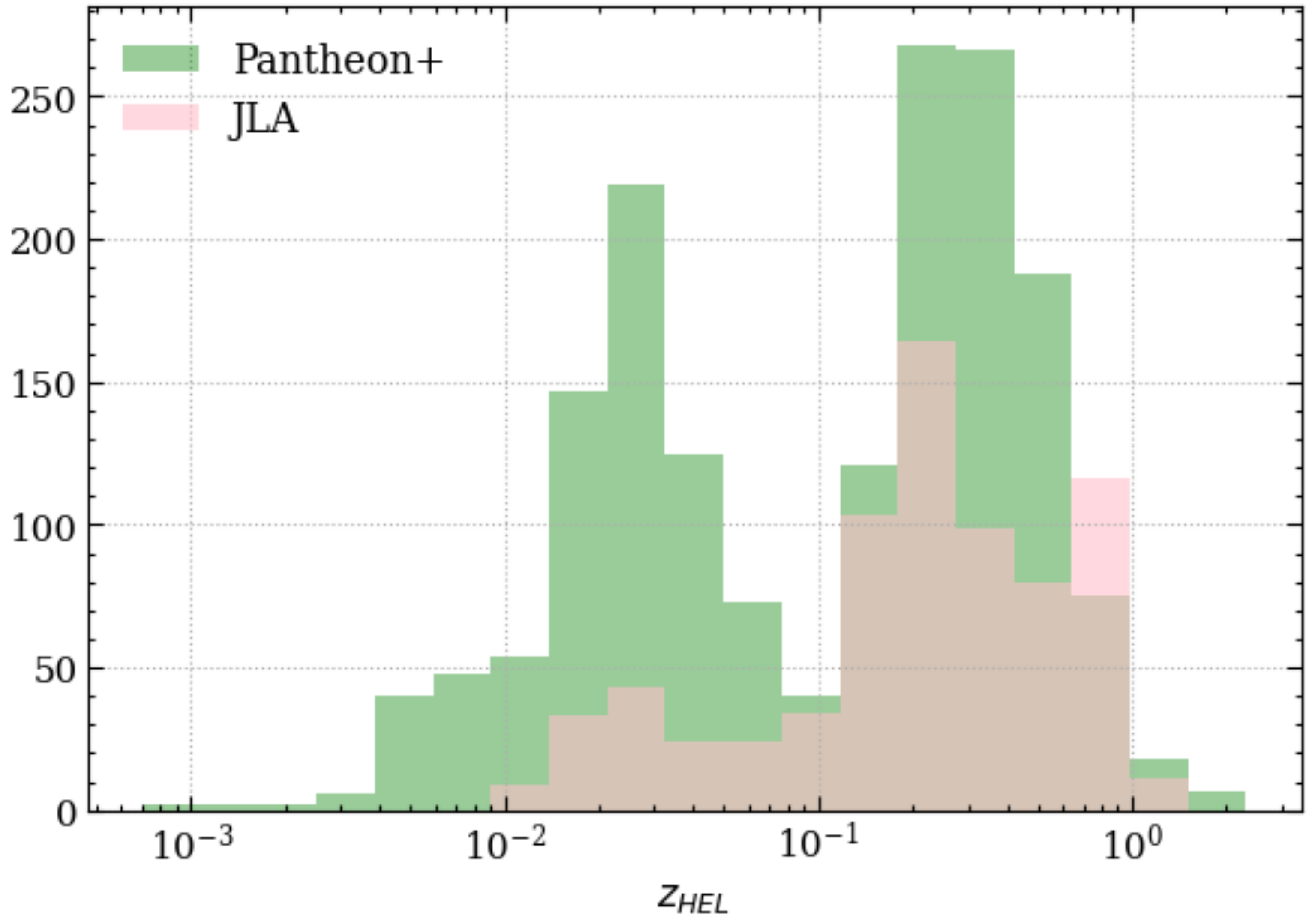
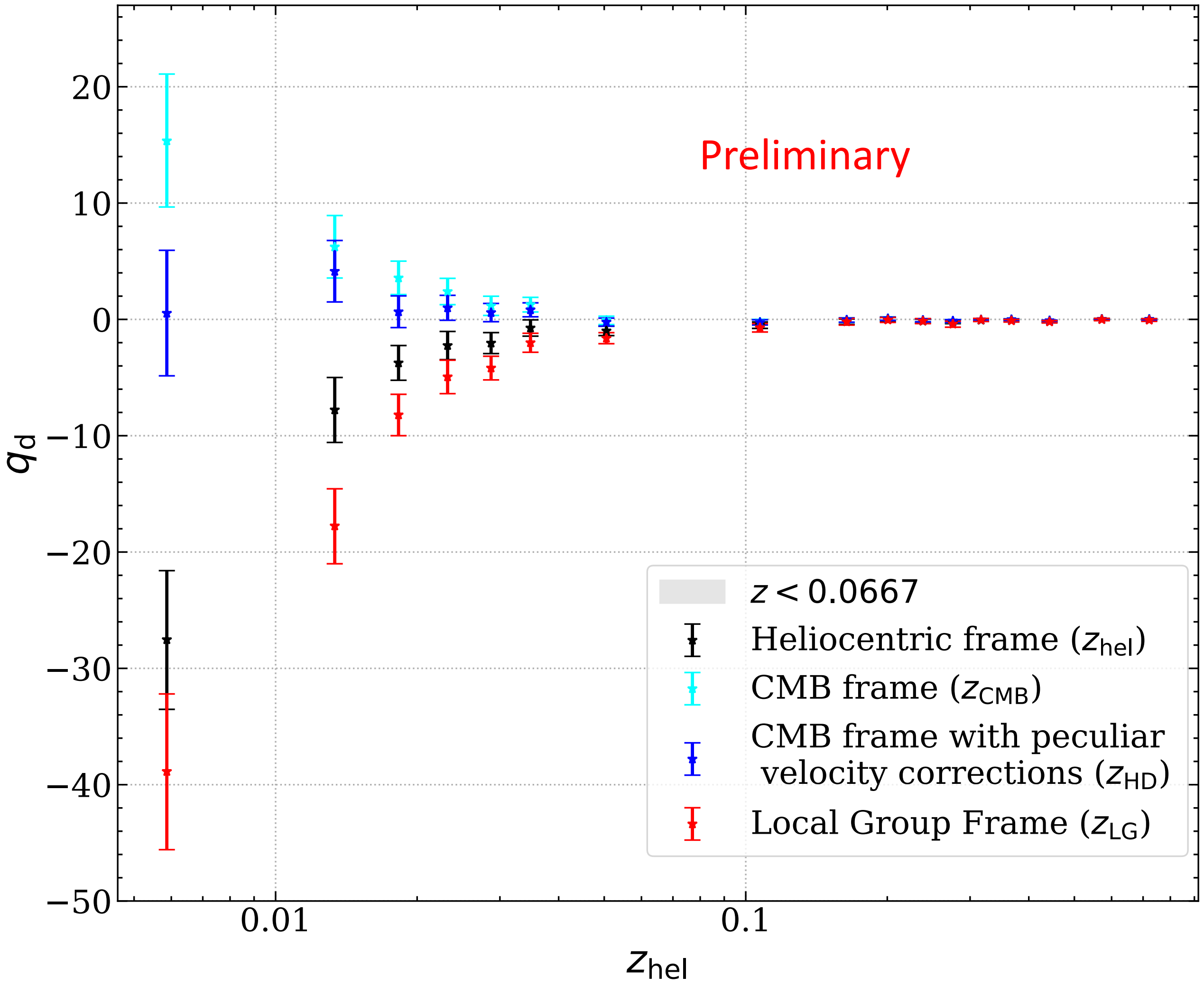
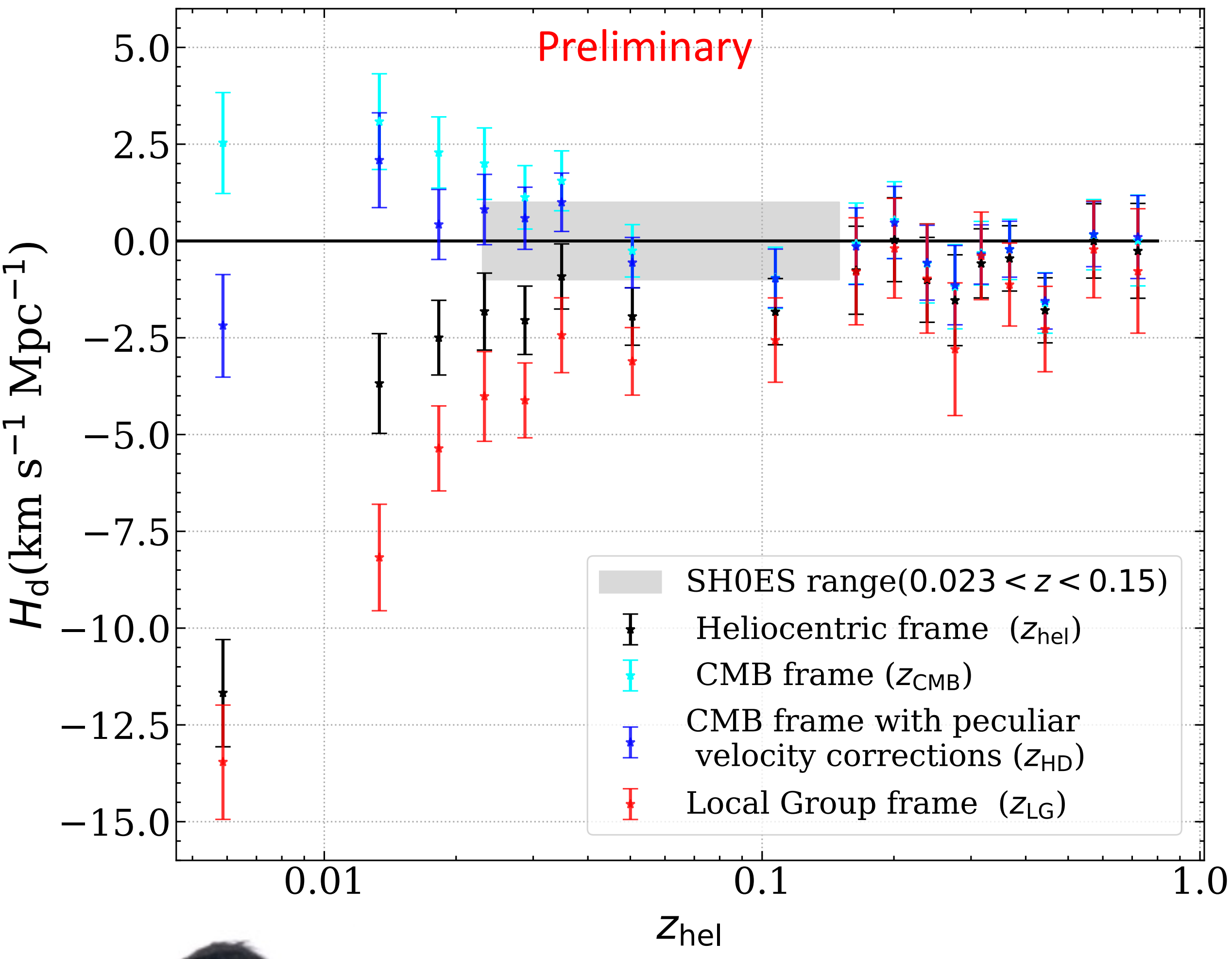


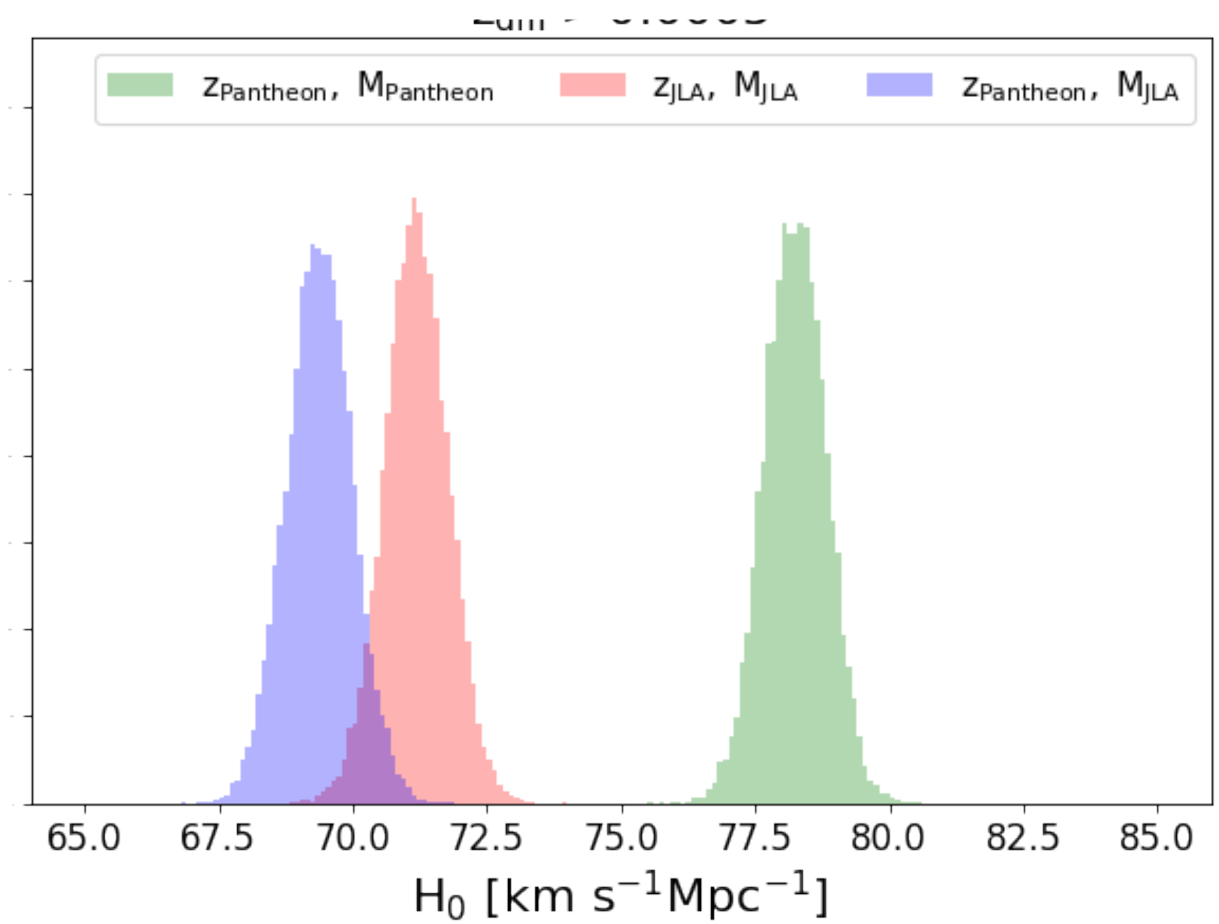
Various changes in terminology



In preparation, Sah et. al. 2024

The Anisotropy on H is greater than the SHOES claimed uncertainty on H





Rameez and Sarkar 2021 *Class. Quantum Grav.* **38** 154005

In preparation, Sah et. al. 2024

The ‘fitting problem’ in cosmology

G F R Ellis† and W Stoeger‡

† School of Mathematics, Queen Mary College, Mile End Road, London E1 4NS, UK and Department of Applied Mathematics, University of Cape Town, Rondebosch 7700, South Africa
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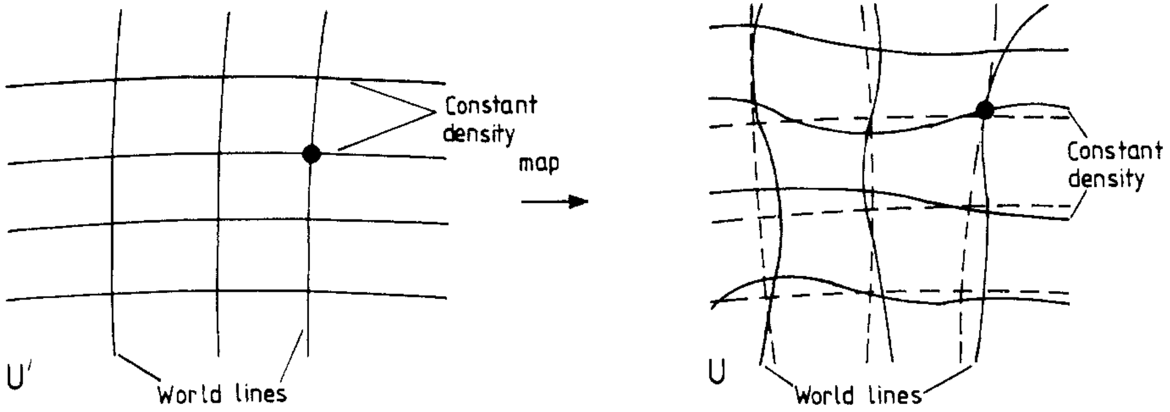
Received 6 February 1987

Abstract. This paper considers the best way to fit an idealised exactly homogeneous and isotropic universe model to a realistic (‘lumpy’) universe; whether made explicit or not, some such approach of necessity underlies the use of the standard Robertson–Walker models as models of the real universe. Approaches based on averaging, normal coordinates and null data are presented, the latter offering the best opportunity to relate the fitting procedure to data obtainable by astronomical observations.



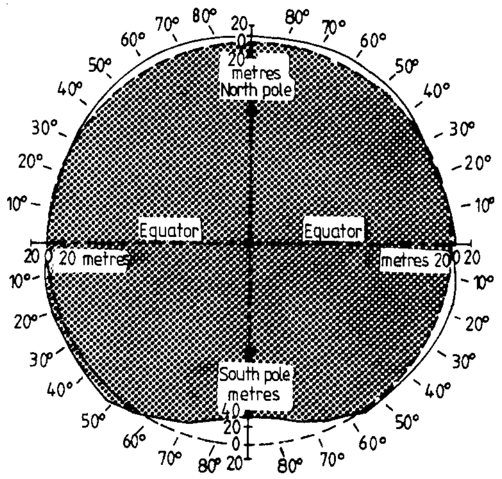


Figure 1. (*a*) An exactly uniform and spherically symmetrical FLRW universe U′ mapped into the lumpy universe U so as to give the best fit possible. (*b*) An exactly spherical sphere fitted to the lumpy world to give the best fit possible.

The Earth is a Sphere to a precision of 50 kms on the radius, but not to a precision of 5 kms

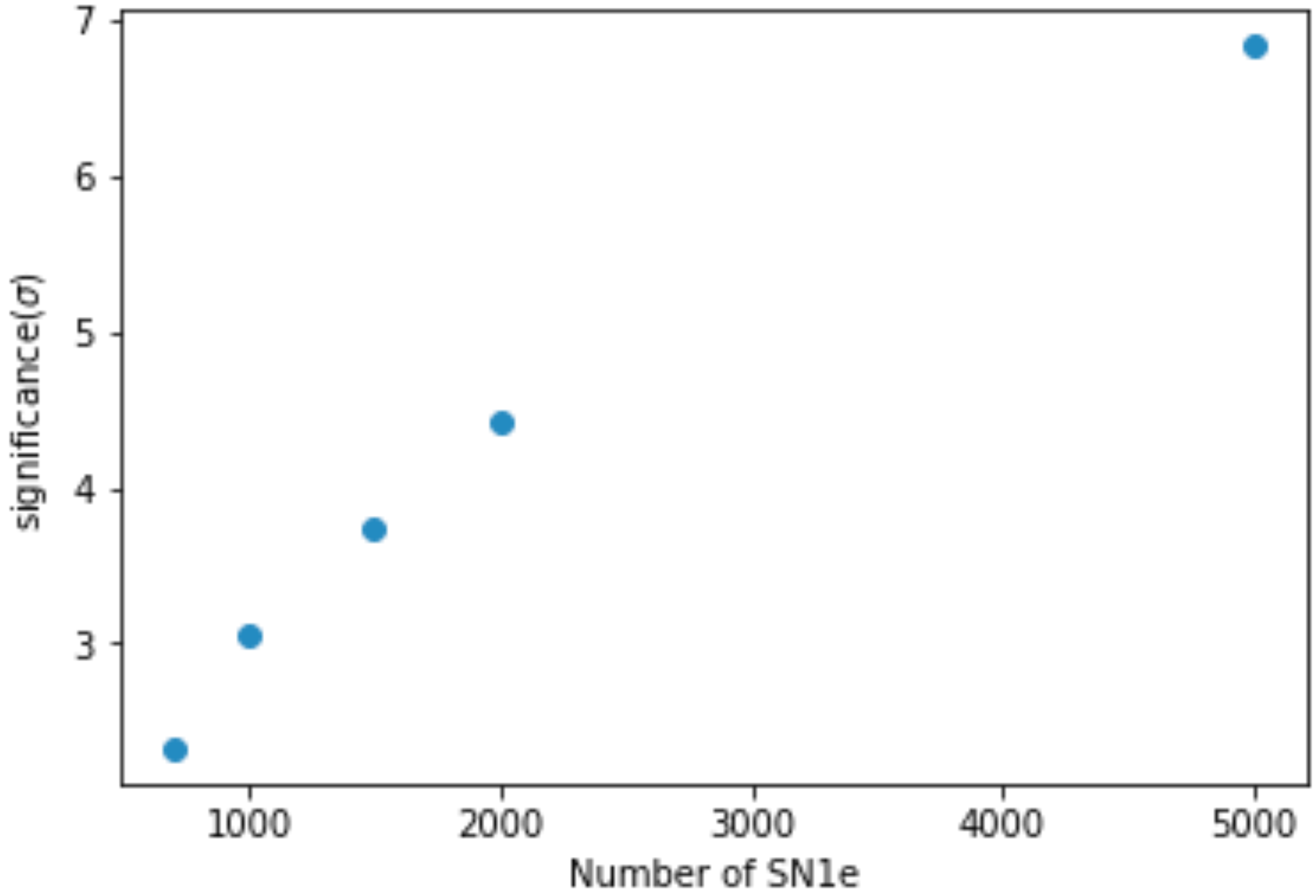
Similarly the Universe is FLRW to a precision of 10 km s^{-1} Mpc^{-1} but not to a precision of 1 km s^{-1} Mpc^{-1}

It is tilted

σ vs N

LSST DESC Project No 254
"testing tilted cosmology"
Modelling and Combined Probes working group

Ongoing : Develop rest frame independent template fitting and calibration pipelines



Median significance at which $q_d = 0$ can be rejected, from 100 simulations of N SNe, using the method of CMRS19

With ~5000 SNe, the null hypothesis can be rejected at more than 6 sigma

Conclusion

The Universe is anisotropic and the Cosmic Rest Frame is a myth

- Ellis & Baldwin tests performed on 4 independent Radio galaxy catalogues and CatWISE Quasars conclusively reject the exclusively kinematic interpretation of the CMB dipole at $> 5\,\sigma$. CMB rest frame and matter rest frame are different. Cosmological principle stands falsified.
- SN1a data are better fit by a "tilted Friedmann model". Ensuing debate stultifies dark energy evidence.
- Strong hint towards the inhomogeneous cosmological models.

A new cosmological tension!

Three projects in LSST DESC
All who have data access are welcome to join

Reviews
Mohayaee, Rameez & Sarkar
Eur.Phys.J.ST 230 (2021) 9, 2067-2076

Subir Sarkar
"Heart of Darkness"
Inference: International Review of Science 6 (2022) 4


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]

Einstein published the general theory of relativity in 1915; and in 1917, he attempted to apply his theory to the cosmos as a whole. The result was a universe that was

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