Anisotropy and the missing rest frame of the Universe

A challenge to the standard cosmological model

M. Rameez

work in coll with:

Secrest, von Hausegger, Colin, Mohayaee, Sarkar

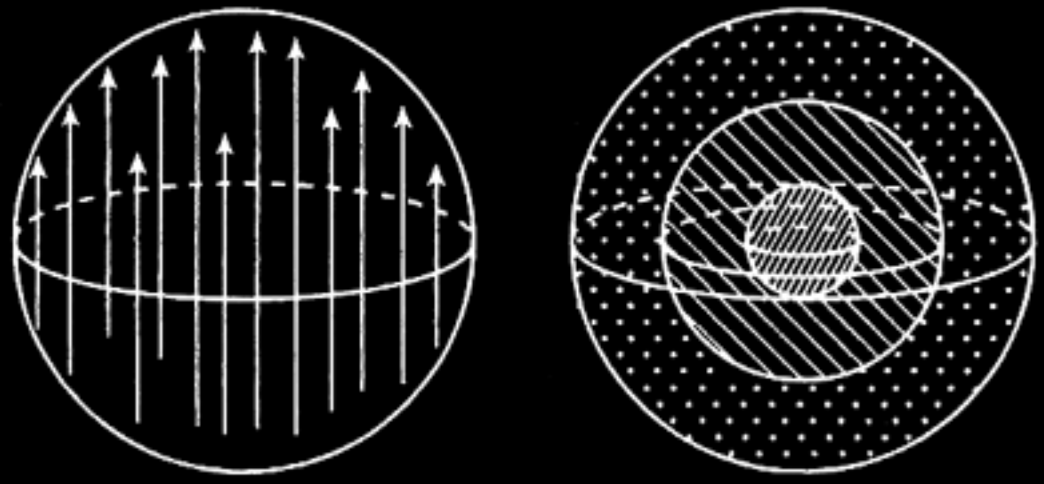
tifr

19th Rencontres du Vietnam

Quy Nhon, Socialist Republic of Vietnam

The cosmological principle

The Universe is (statistically) isotropic and homogenous (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.

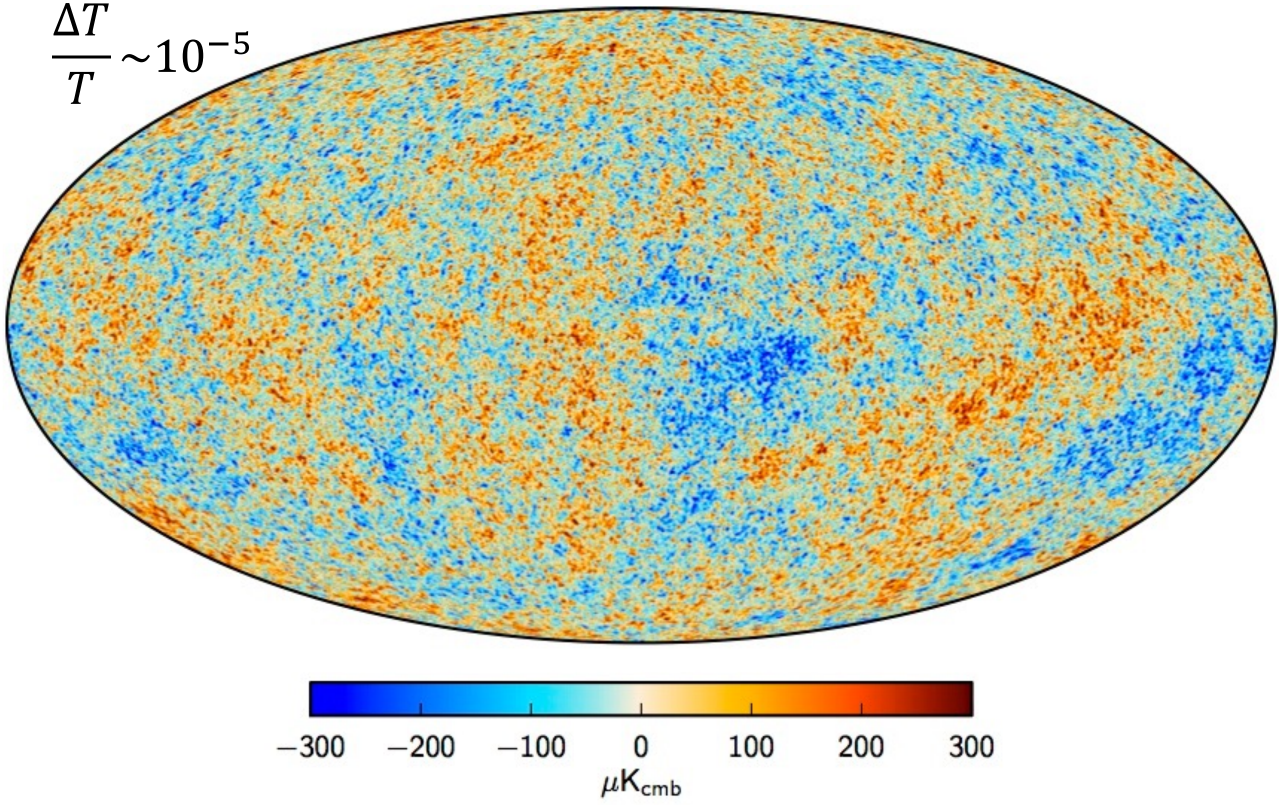
THE 'PERFECT' VERSION WAS ABANDONED FOLLOWING THE DISCOVERY OF THE CMB IN 1964 AND THE REALIZATION THAT THE UNIVERSE *DOES* HAVE A BEGINNING ... BUT THE COSMOLOGICAL PRINCIPLE LIVED ON

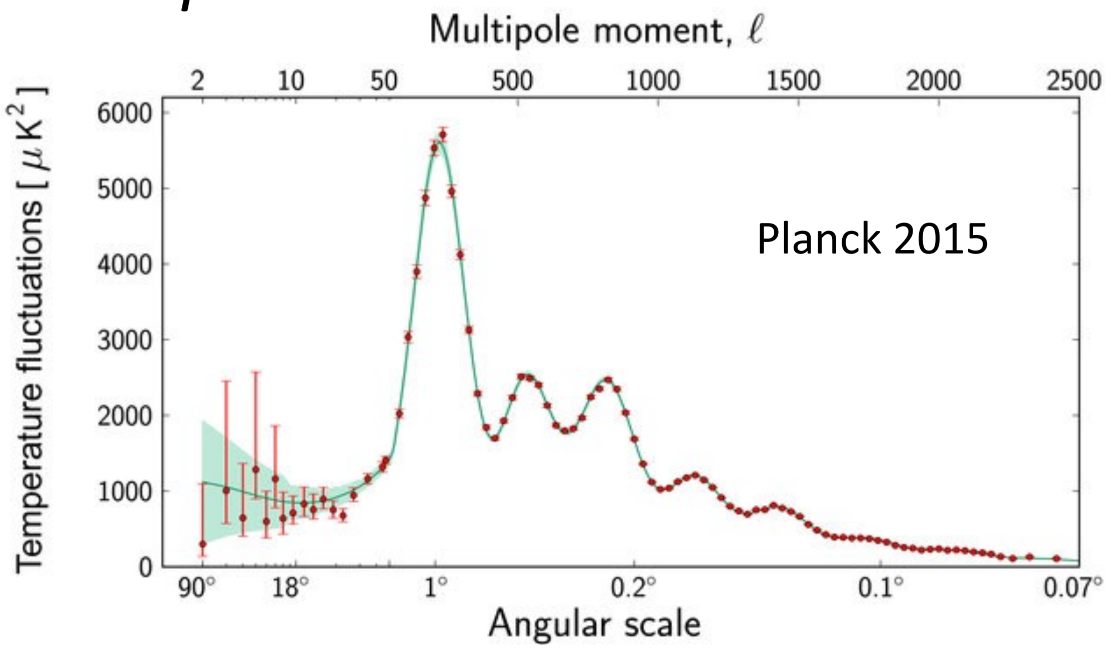
> The real reason, though, for our adherence here to the Cosmological Principle is not that it is surely correct, but rather, that it allows us to make use of the extremely limited data provided to cosmology by observational astronomy. …
>
> … If the data will not fit into this framework, we shall be 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)

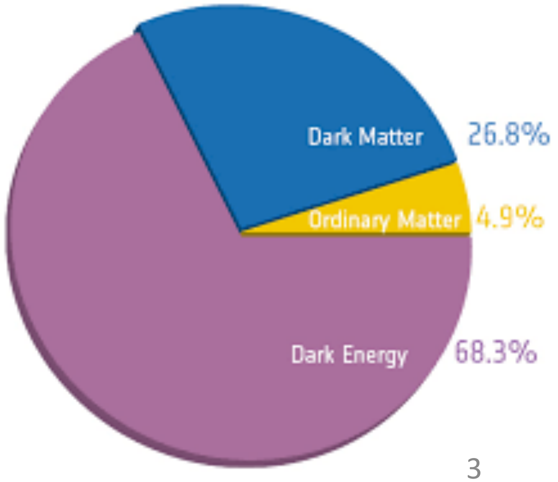
“Data from the Planck satellite show the Universe to be highly isotropic”

T = 2.725 K

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

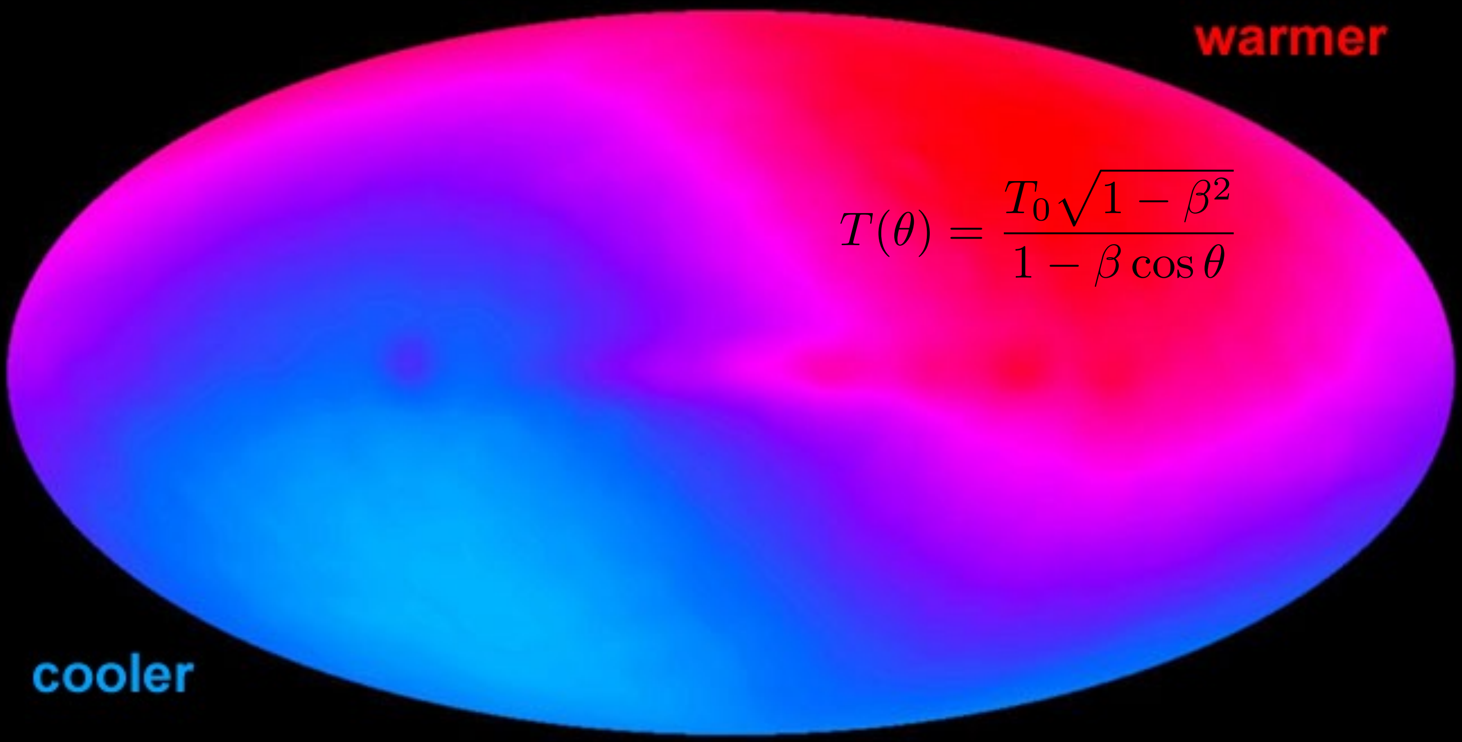






We observe a statistically isotropic Gaussian random field of small temperature fluctuations (fully quantified by the 2-point correlations ➝ angular power spectrum)

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

- Motion of the Sun around the Galaxy ~225 +/- 18 km/s
- The motion of the Local Group 627+/-22 km/s ApJ, 709, 483

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

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

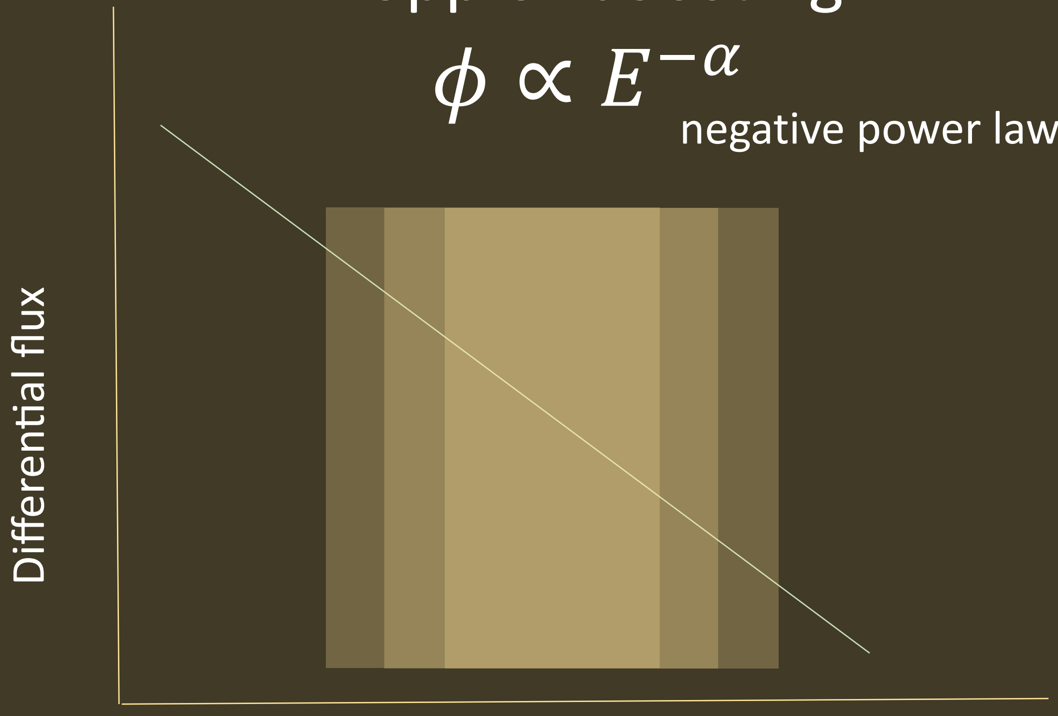
Observer, velocity v

+

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.

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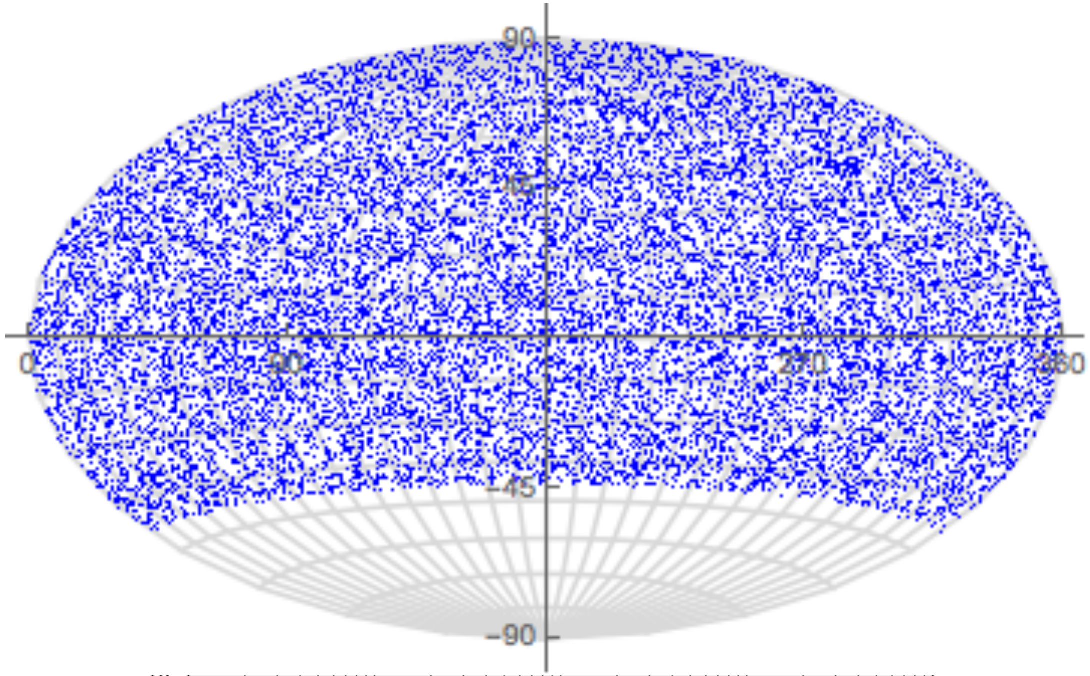
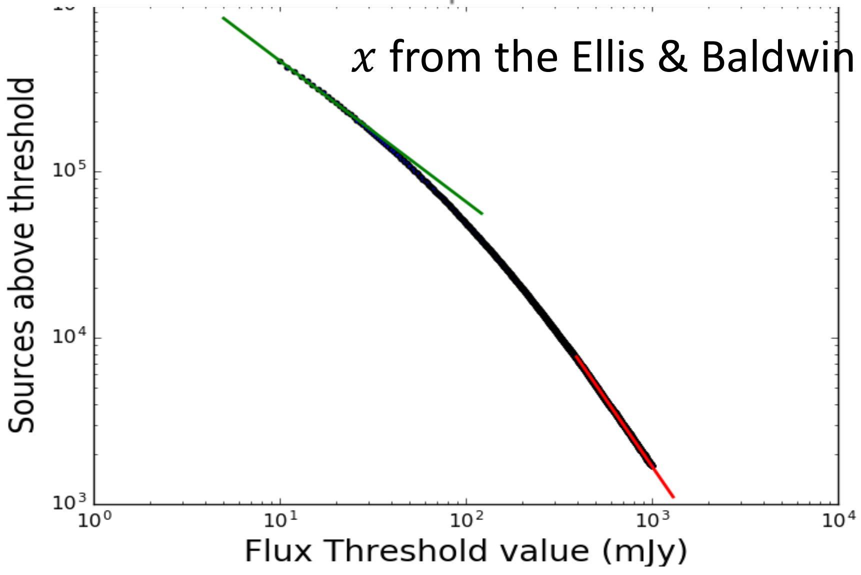
The situation anticipated by Ellis and Baldwin in 1984 now confronts us!

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^o

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

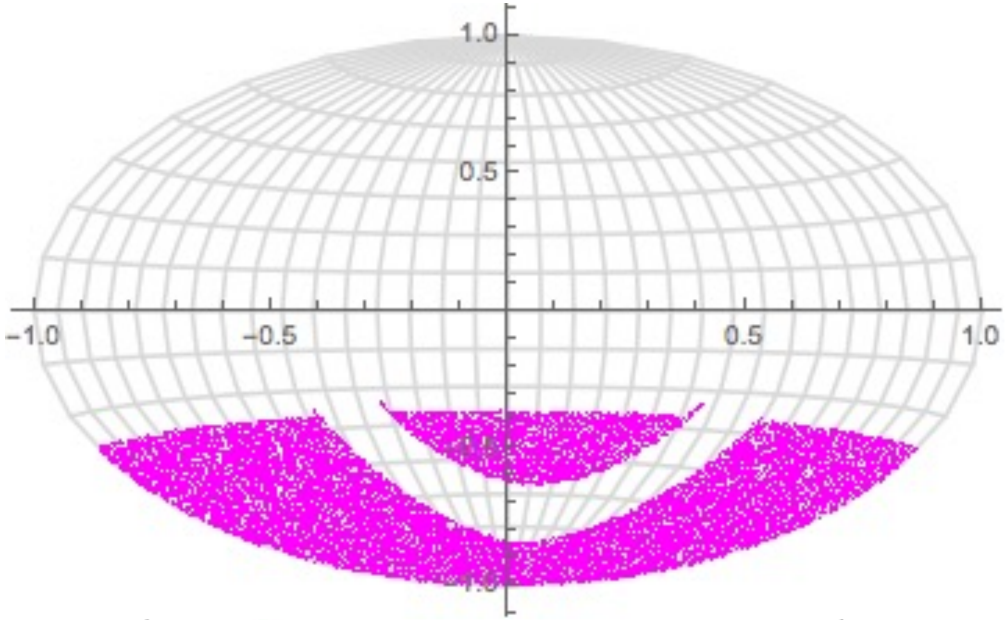


x from the Ellis & Baldwin expression

Phys. Rev. D, 78, 043519

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

Sydney University Molonglo Sky Survey (SUMSS)

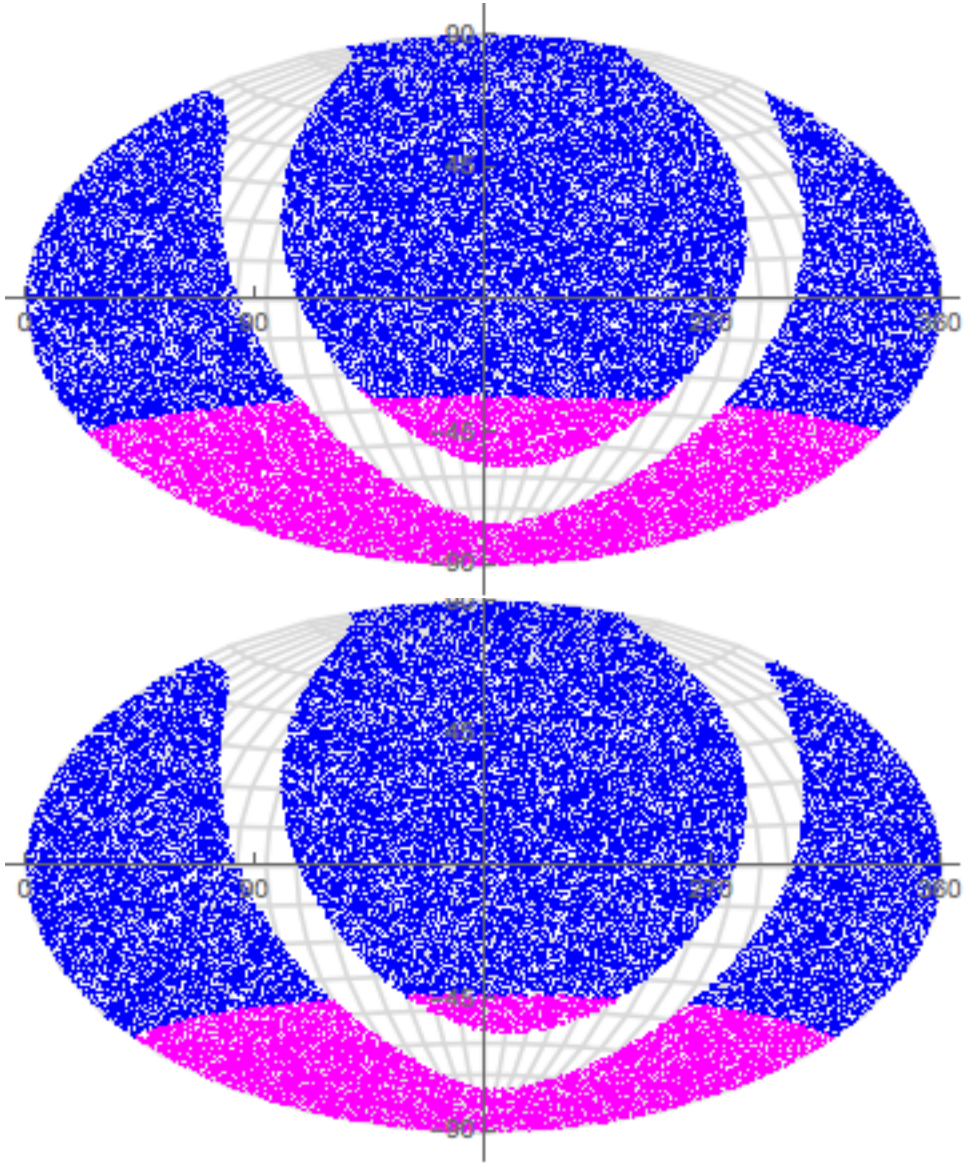


x from the Ellis & Baldwin formula

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

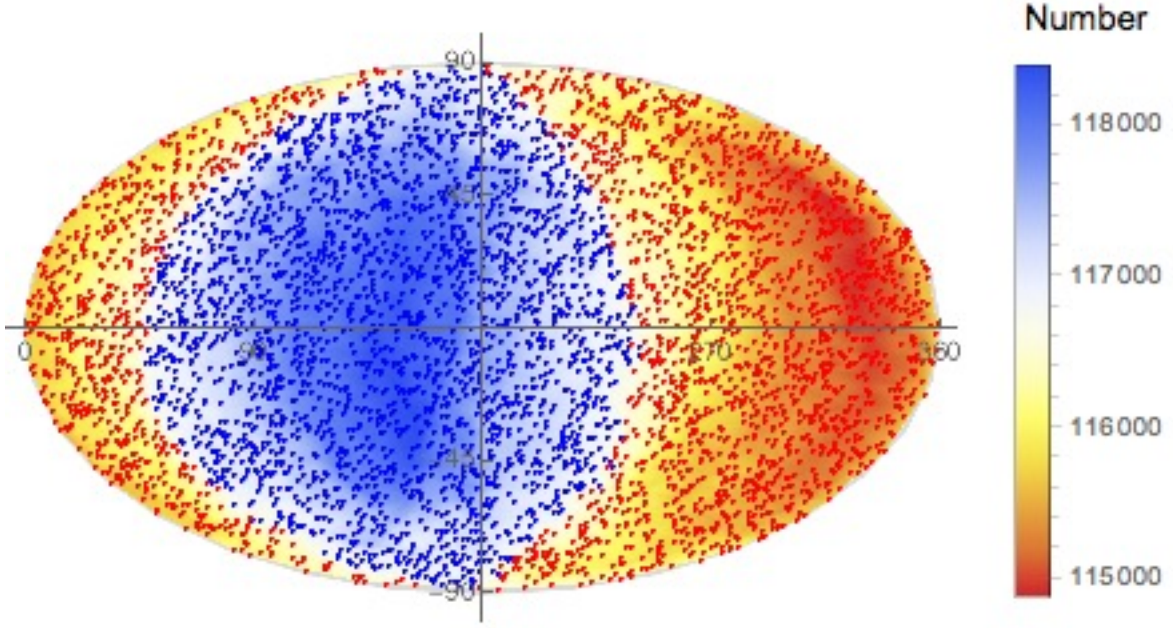
211050 radio sources. Similar sensitivity and resolution to NVSS

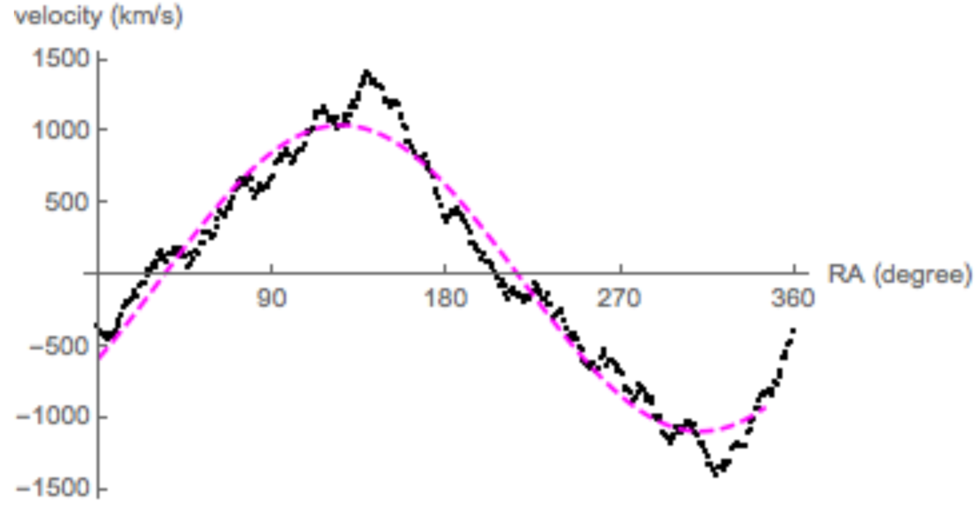
The NVSUMSS-Combined All Sky catalog



- 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 !

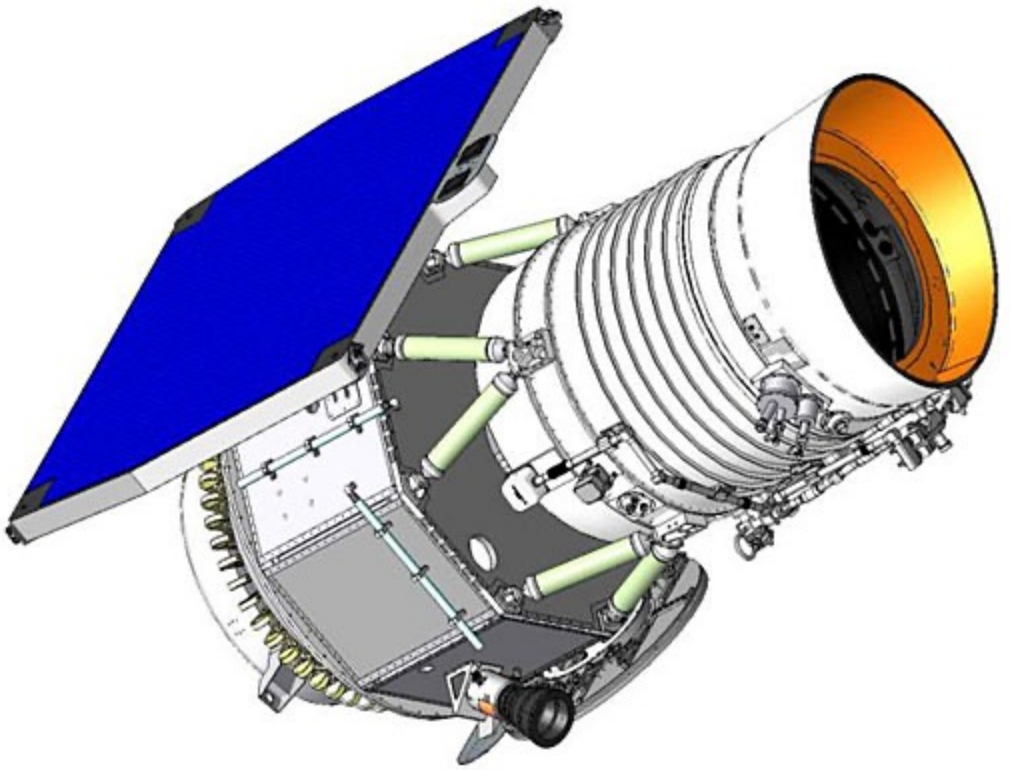
SKA phase 1 measurement ~10%

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

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

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

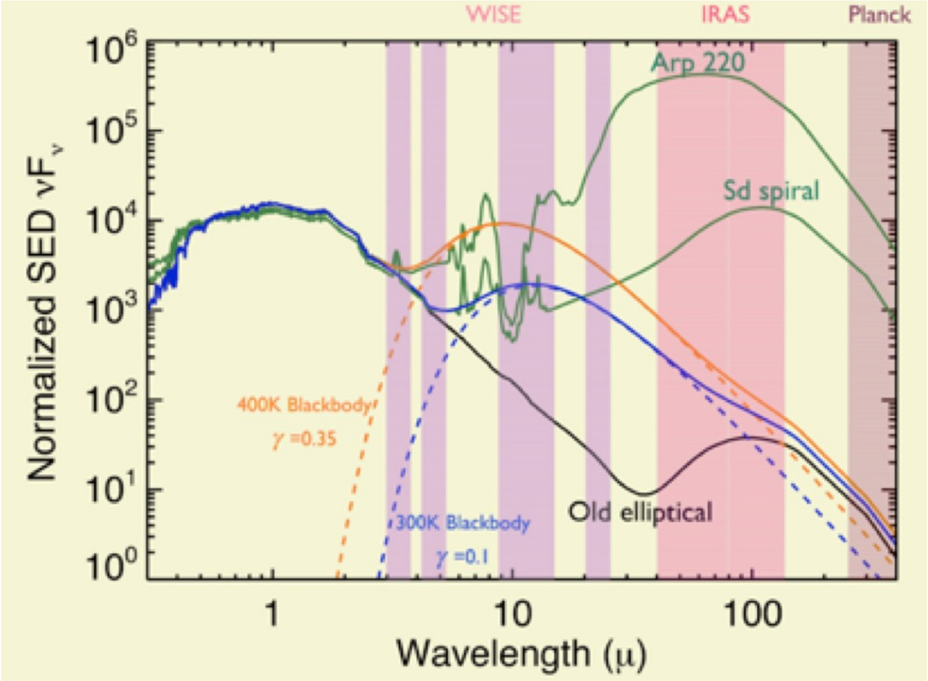
The Widefield Infrared Survey Explorer



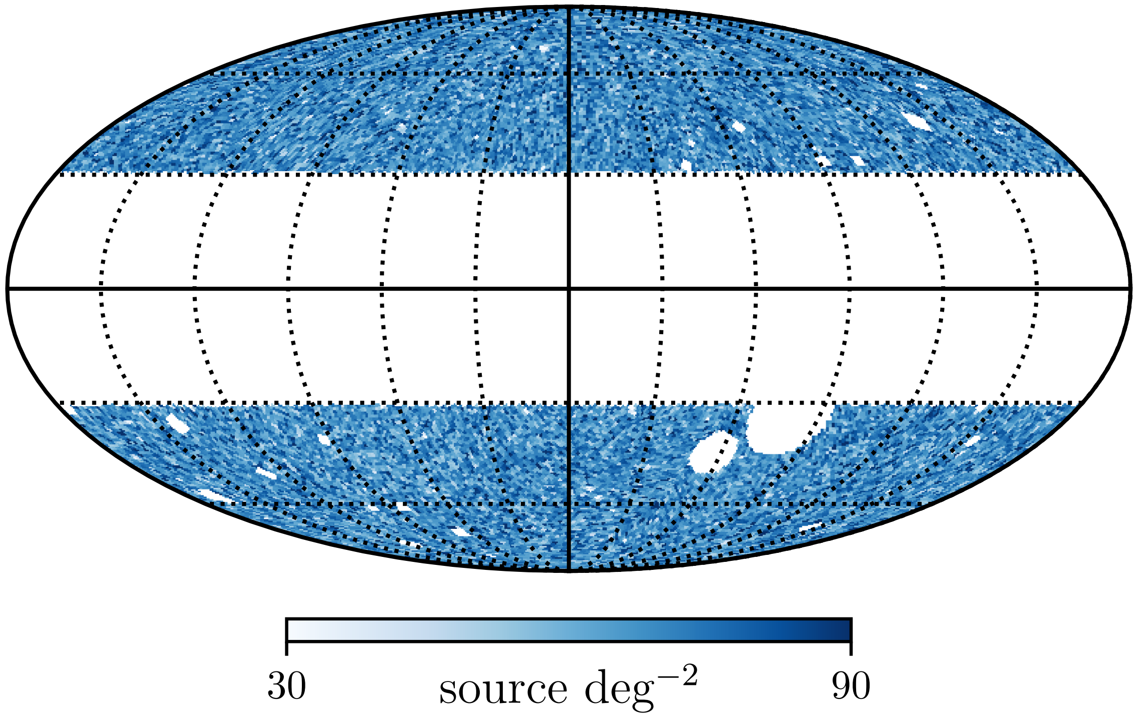
All sky infrared survey over 10 months, in the bands 3.4, 4.6, 12 and 22 μm using a 40 cm diameter telescope

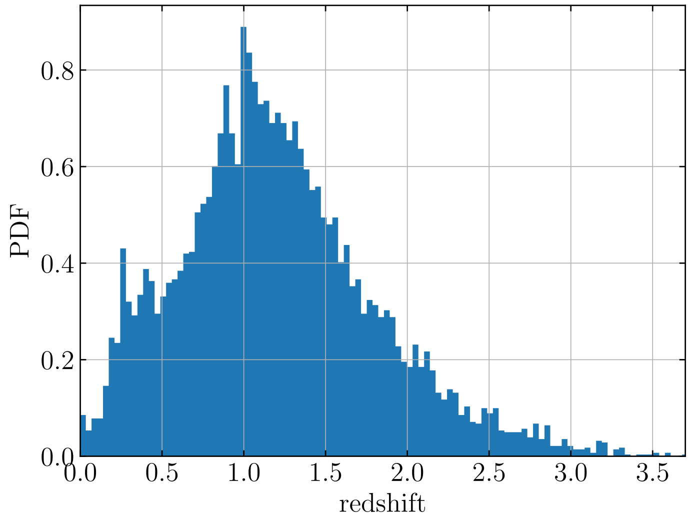
Generated a catalog of 746 million+ objects, most of which are stars.

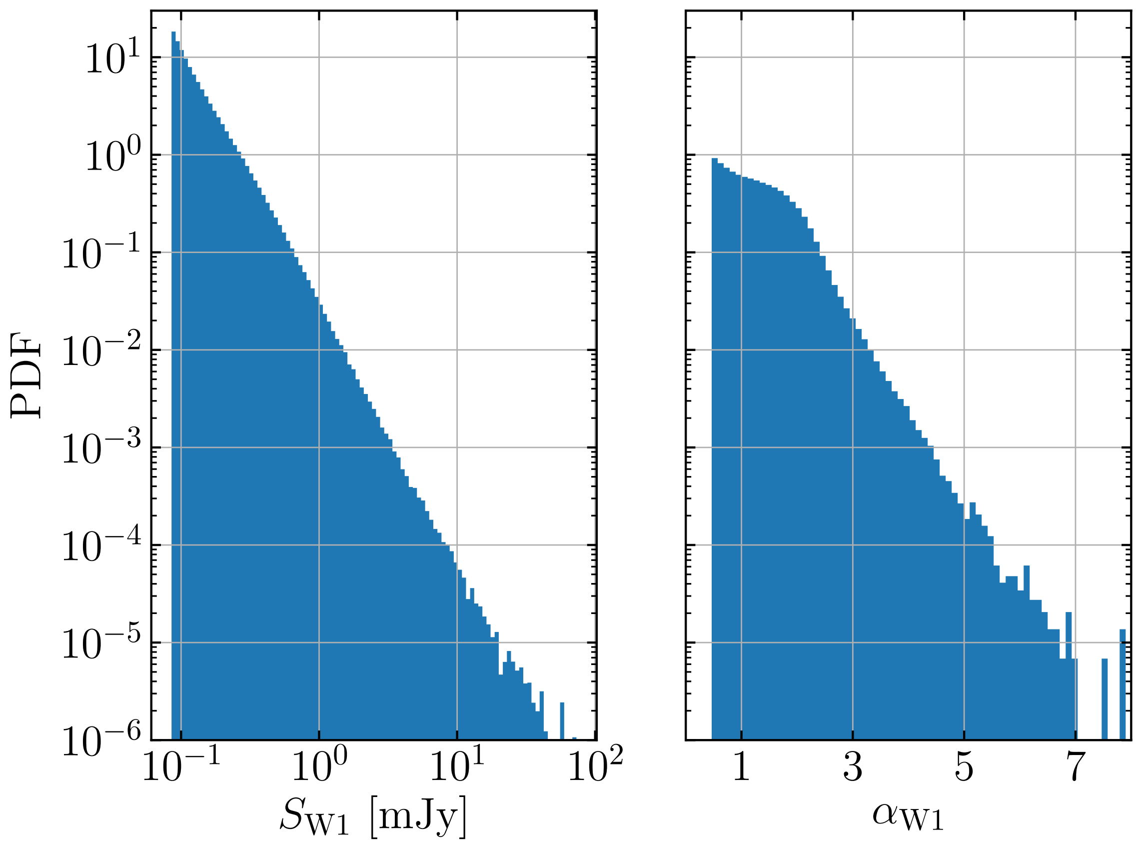
Directionally unbiased survey strategy, arc second angular resolution, multi band photometry.



CatWISE AGN 1355352 sources

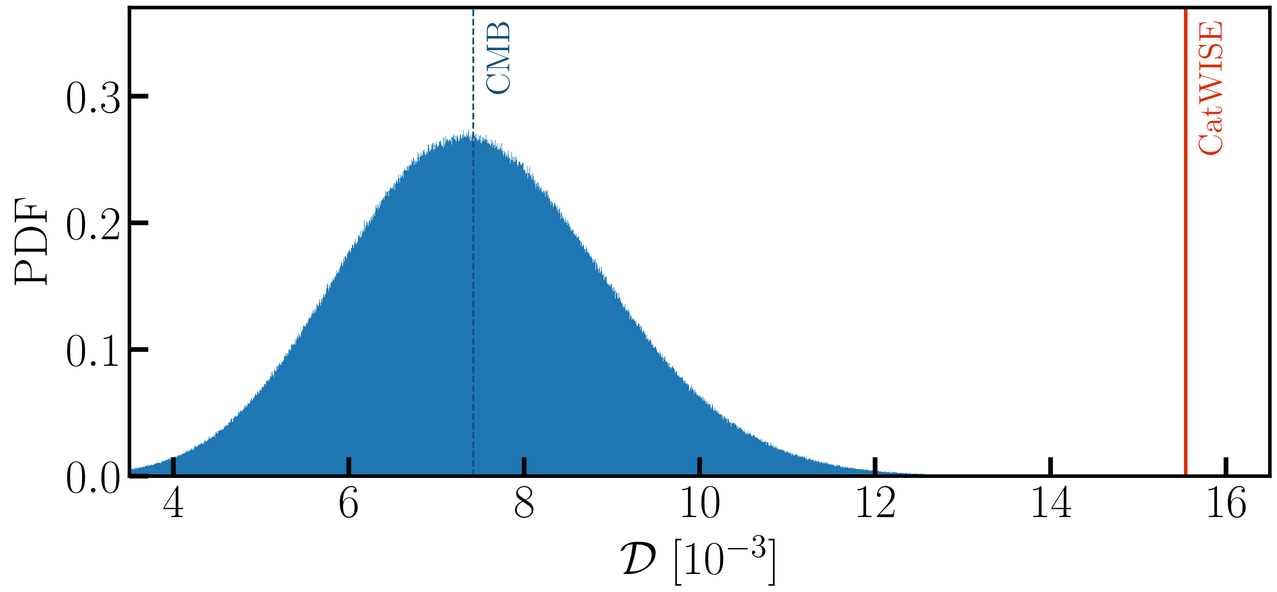


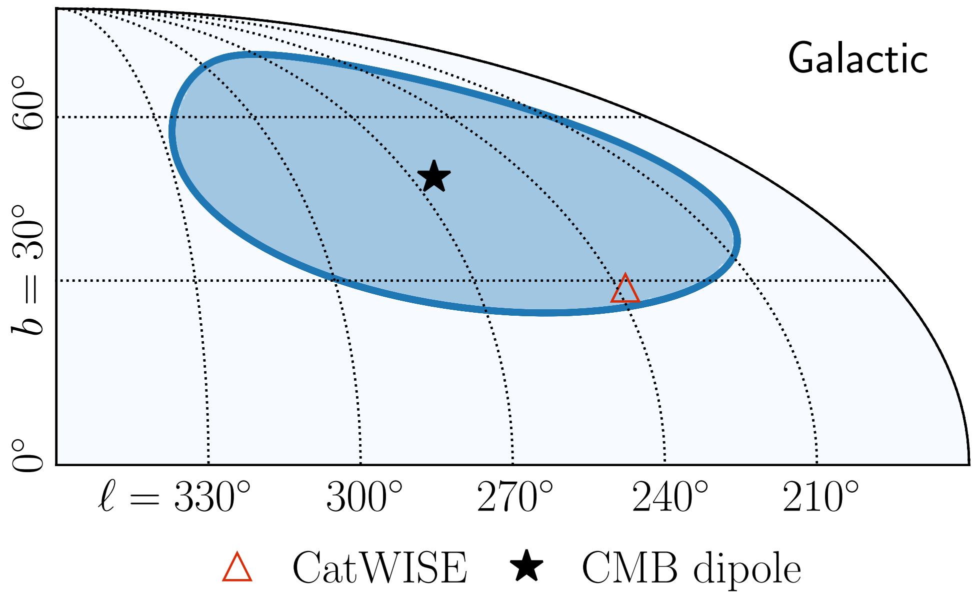




Astrophys.J.Lett. 908 (2021) 2, L51

Results

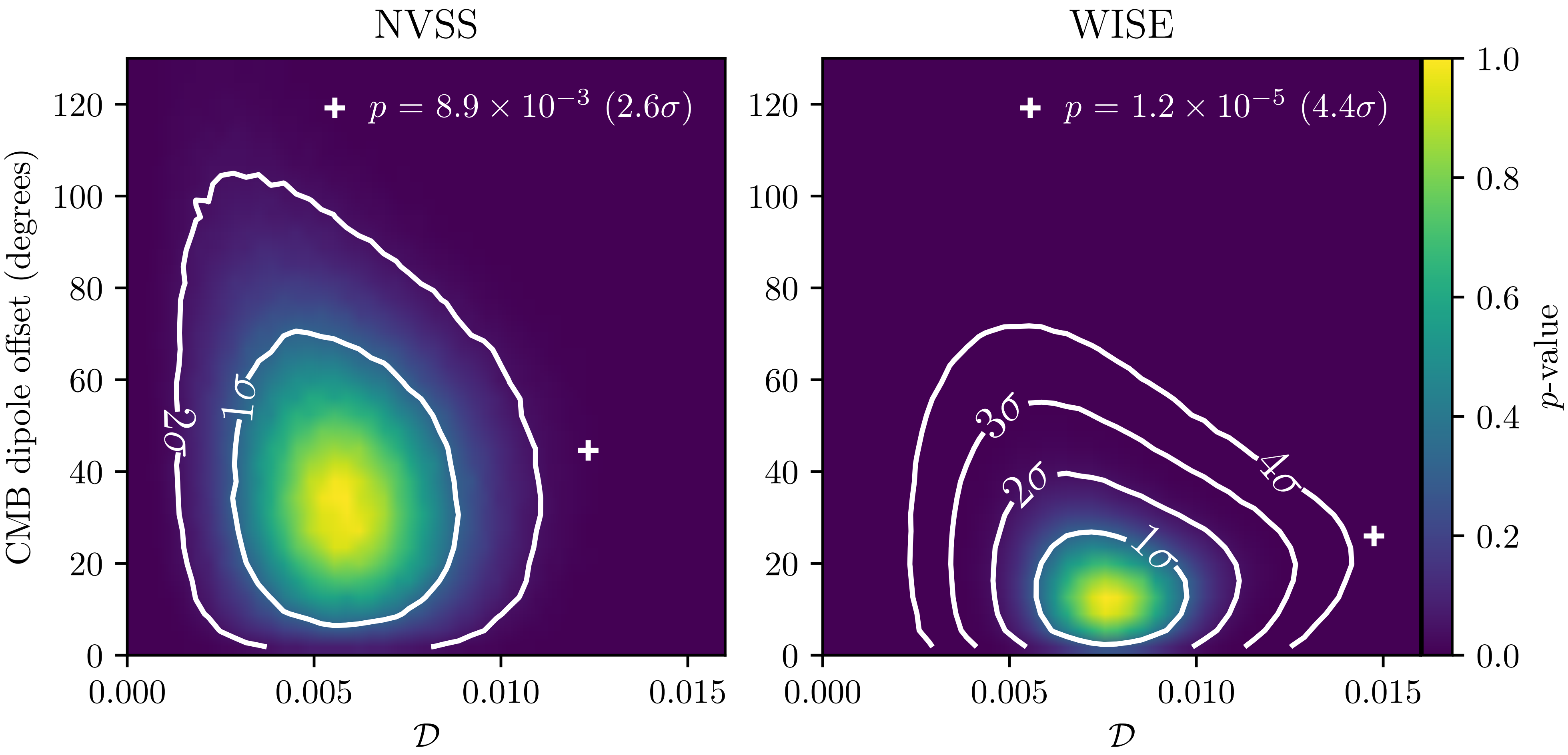




p = 5 $\times 10^{-7}$ (4.9 σ)

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

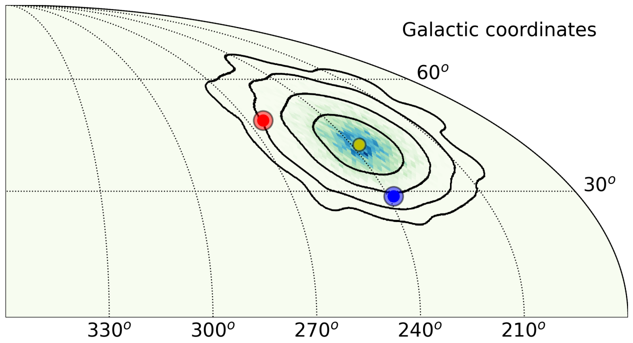
https://zenodo.org/record/4448512



Conservative Sample size weighted Z-scores : 5.1 σ

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

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]

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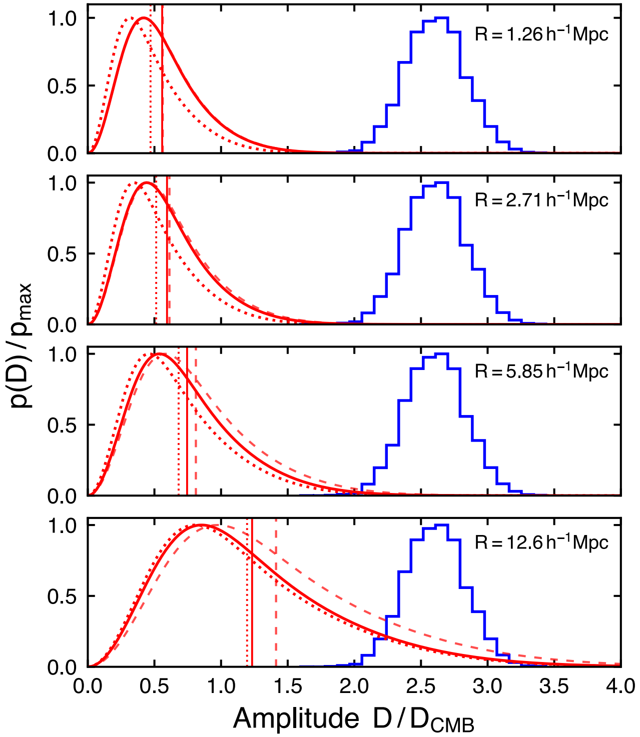
Accepted XXX. Received YYY; in original form ZZZ



ABSTRACT

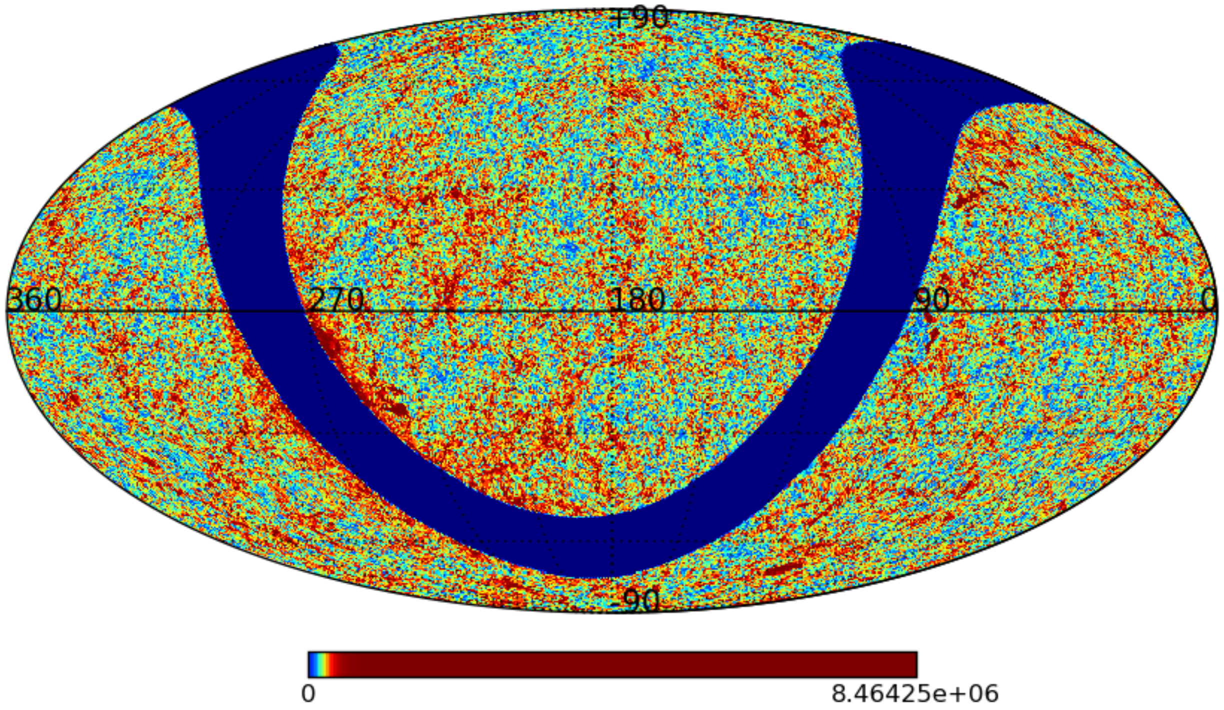
The Cosmological Principle, that the Universe is homogeneous and isotropic on sufficiently large scales, underpins the standard model of cosmology. However, a recent analysis of 1.36 million infrared-selected quasars has identified a significant tension in the amplitude of the number-count dipole compared 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 σ. 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.

Key words: cosmology: large-scale structure of universe — cosmology: cosmic background radiation — cosmology: observations — quasars: general — galaxies: active

AllWISE-Galaxies

following from MNRAS448,1305–1313 (2015)

- Magnitude cuts in different bands, Galactic plane cut at +/-15 degrees
  - Sample of 2.46 million Galaxies, 76% complete, with 1.8% star contamination



Cross correlate with deep surveys over a very narrow sky (SDSS, GAMA) to determine how many are stars and how many are Galaxies

The maximum is in the direction (AllWISE)
237.4° RA, -46.6 ° Dec
331.9° l 6.02° b

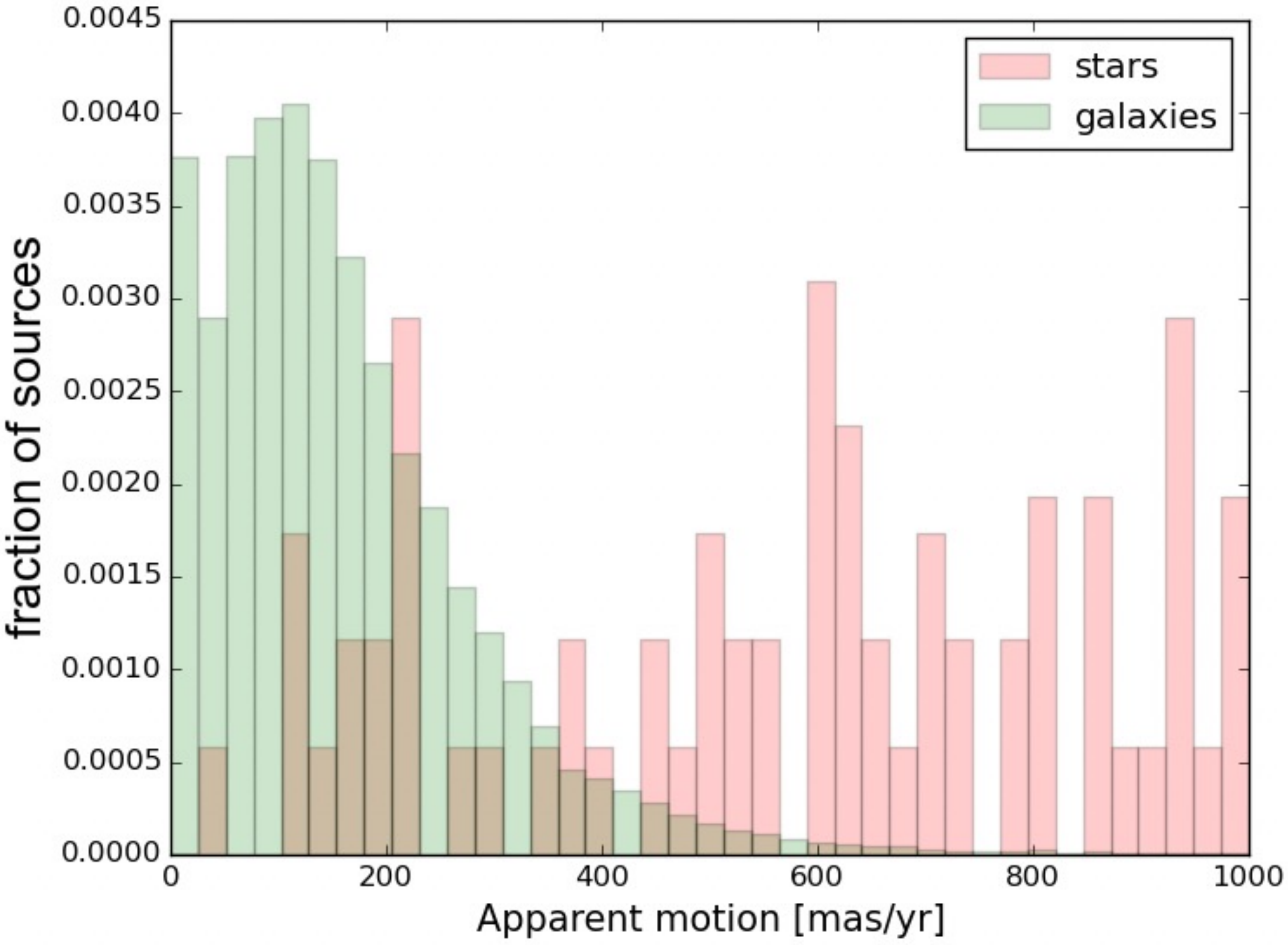
110 degrees from the CMB direction

Dipole magnitude ~0.049

Fully kinematic interpretation ~6000 km/s

in agreement with MNRAS 445 (2014) L60-L64

Getting rid of the stars



Apparent motion = parallax + proper motion

Stars in the Galaxy have higher apparent motions 400 mas/yr up to many arc seconds/ year

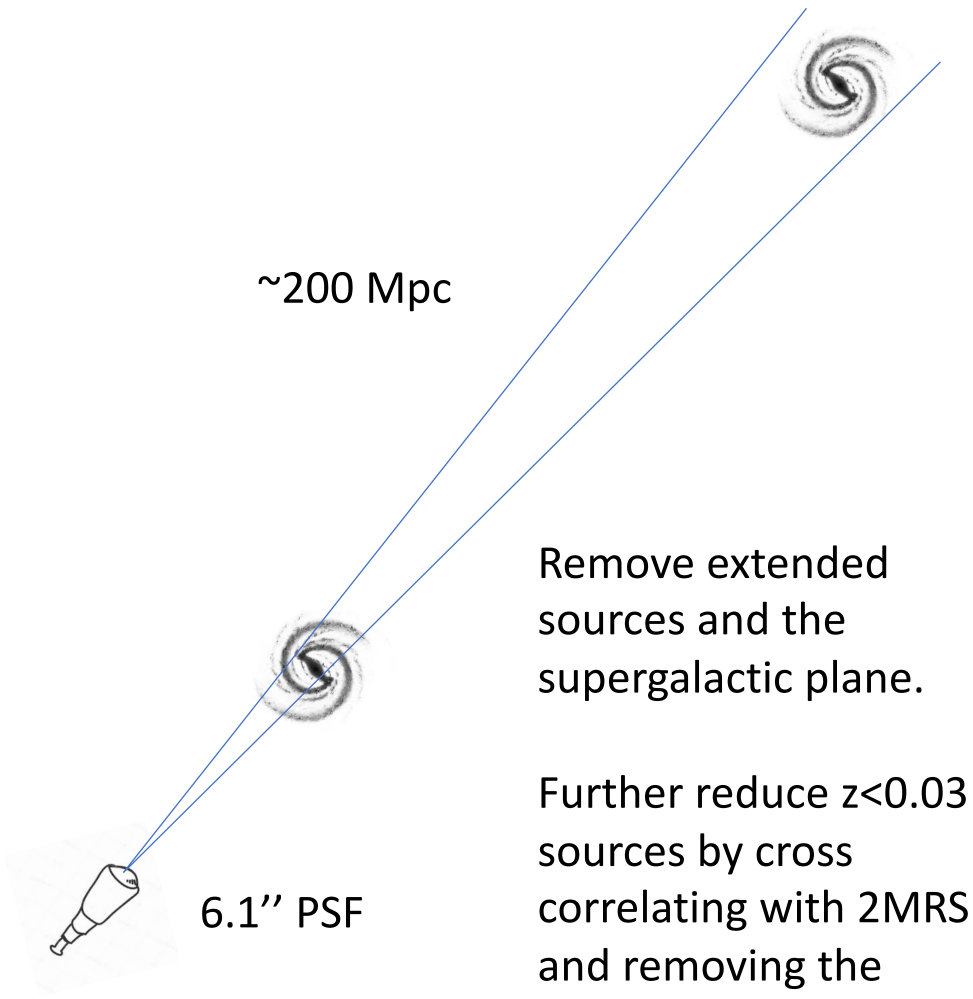
Cuts on apparent motion can bring star contamination down to 0.1%, while still keeping ~1.8 millin galaxies.

182.9° RA, -55.6° DEC, 50.1° from the CMB

Dipole magnitude reduces to 0.014

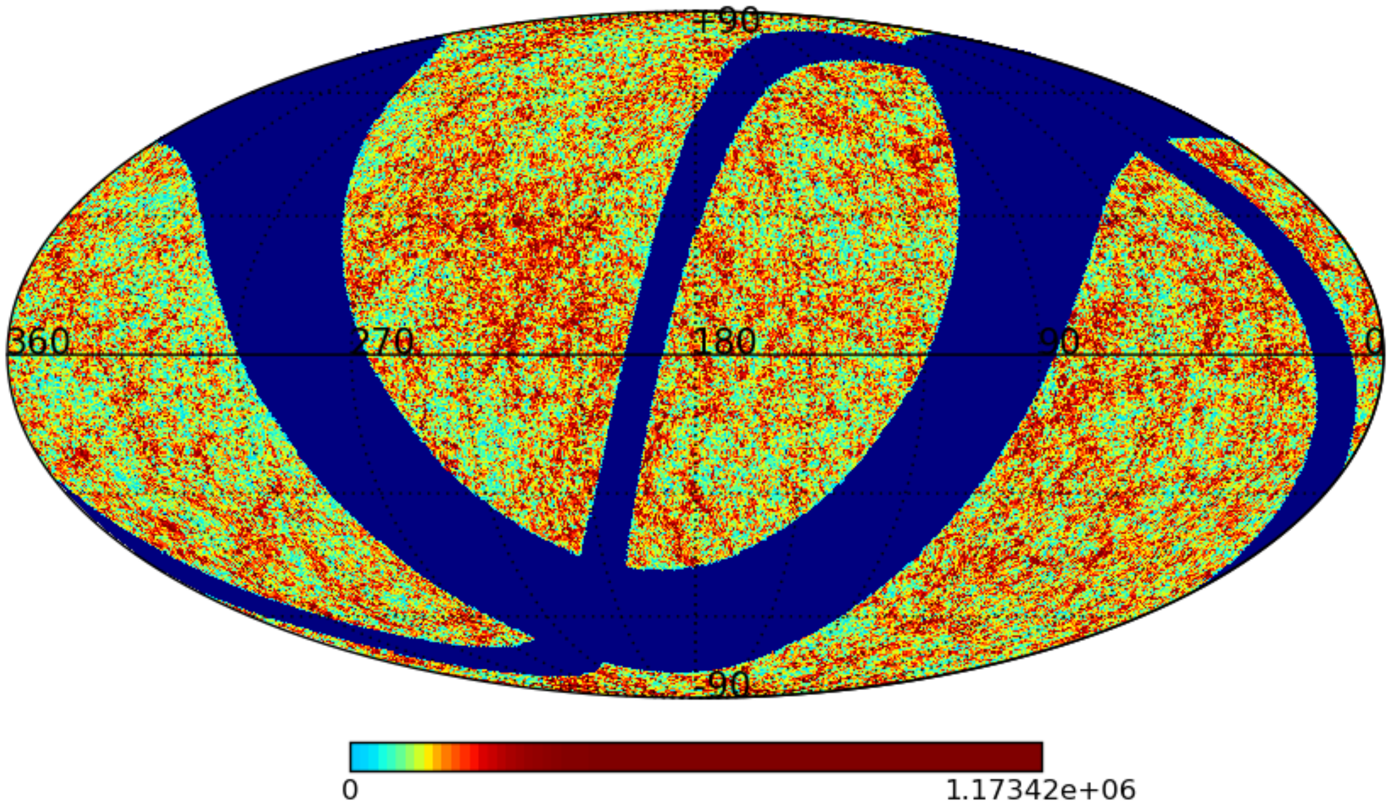
Star galaxy identification by cross correlating with SDSS

Suppressing local anisotropies

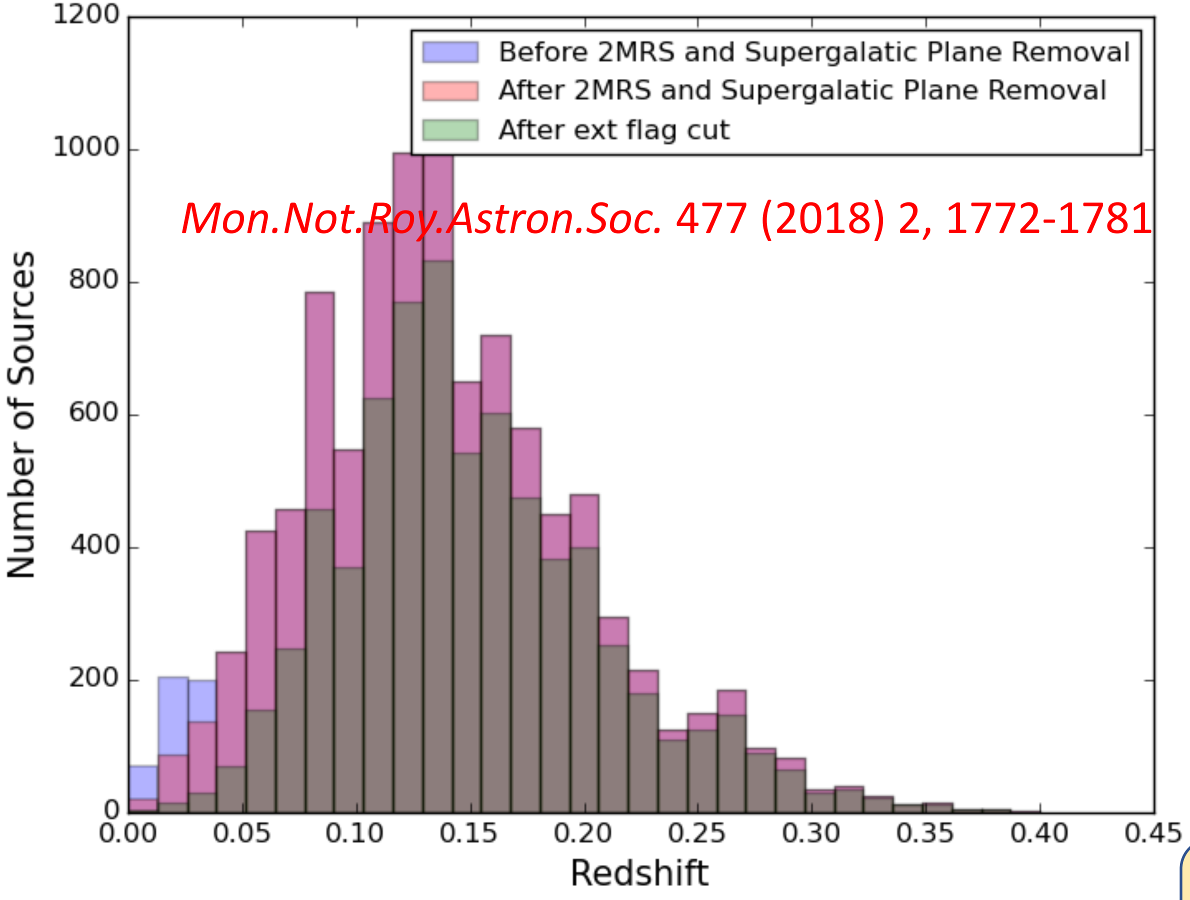


Remove extended sources and the supergalactic plane.

Further reduce z<0.03 sources by cross correlating with 2MRS and removing the correlated sources.



1192182 - AllWISE Galaxies



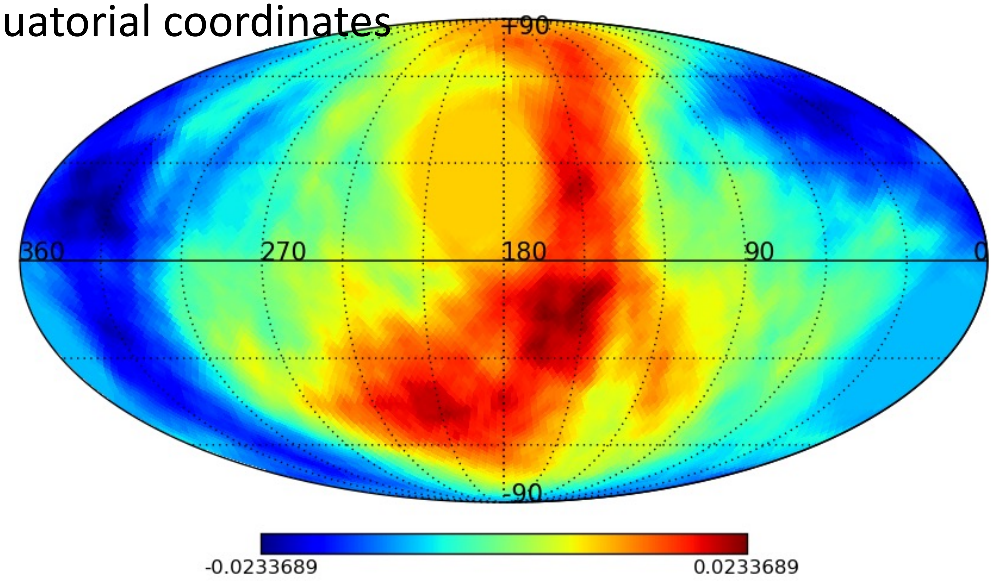
Mon.Not.Roy.Astron.Soc. 477 (2018) 2, 1772-1781

d = 0.0124 > 3600 km/s if fully kinematic

172.6° RA, -6.6° Dec (~4.5° from CMB dipole)

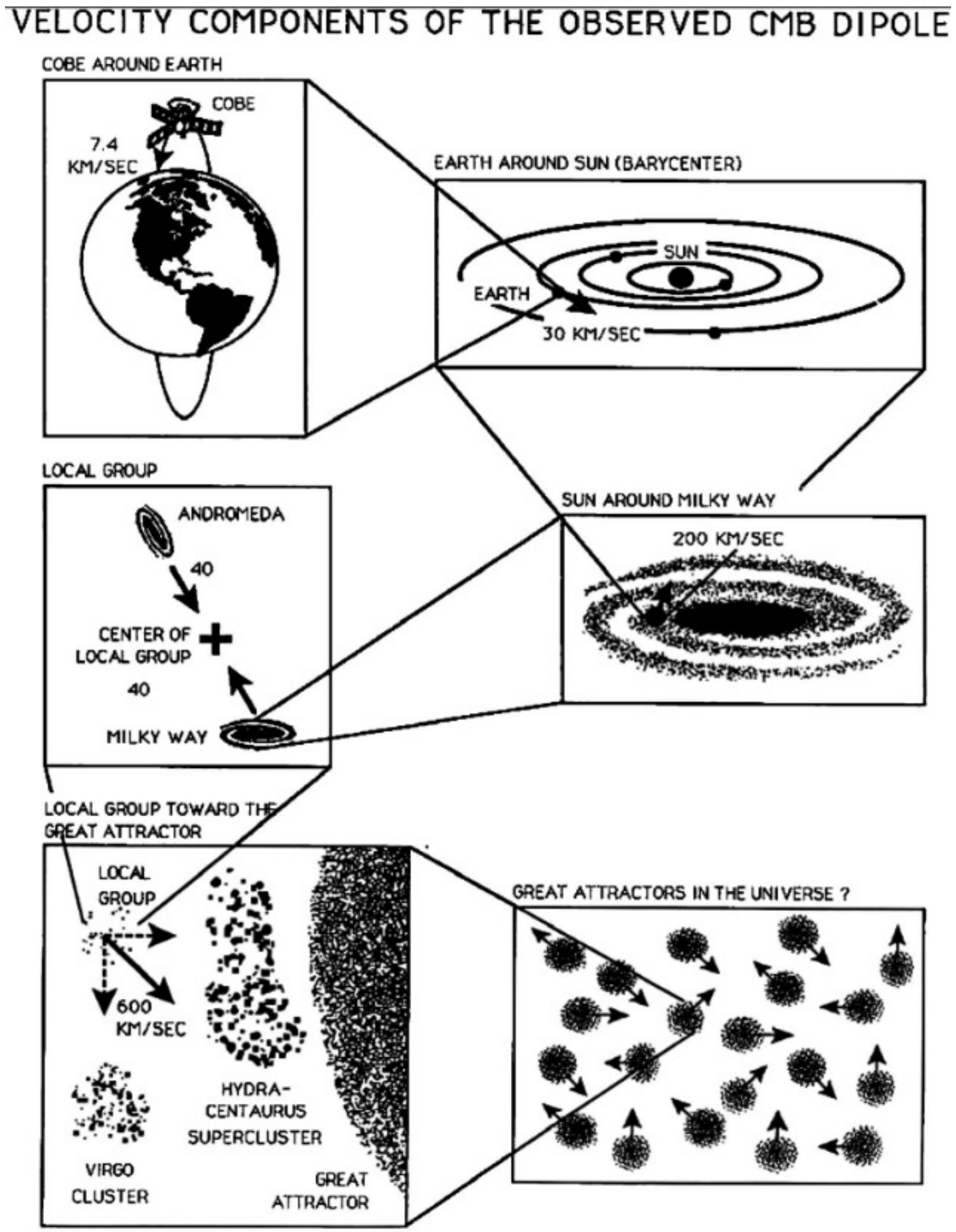
4.6σ statistically significant.

Equatorial coordinates



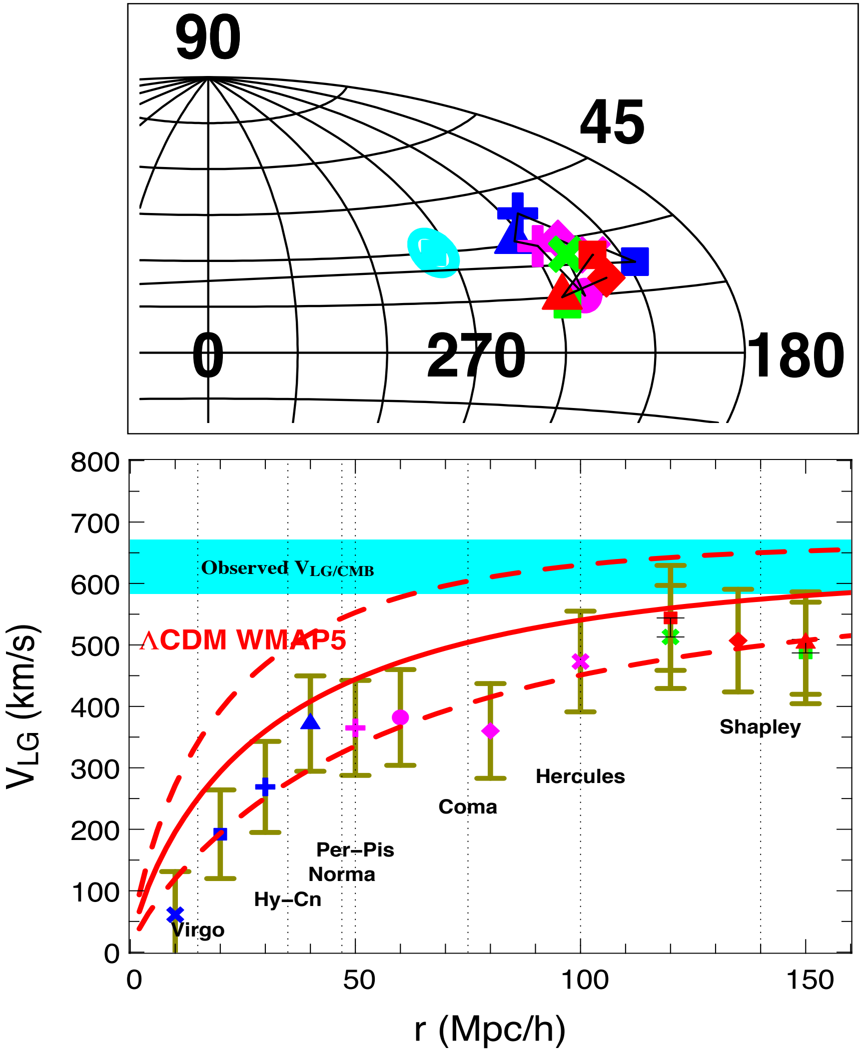
By cross correlating with Galaxy and Mass Assembly

V = 1260 $\pm$ 629 km/s within 6 degrees of CMB dipole
Low redshift

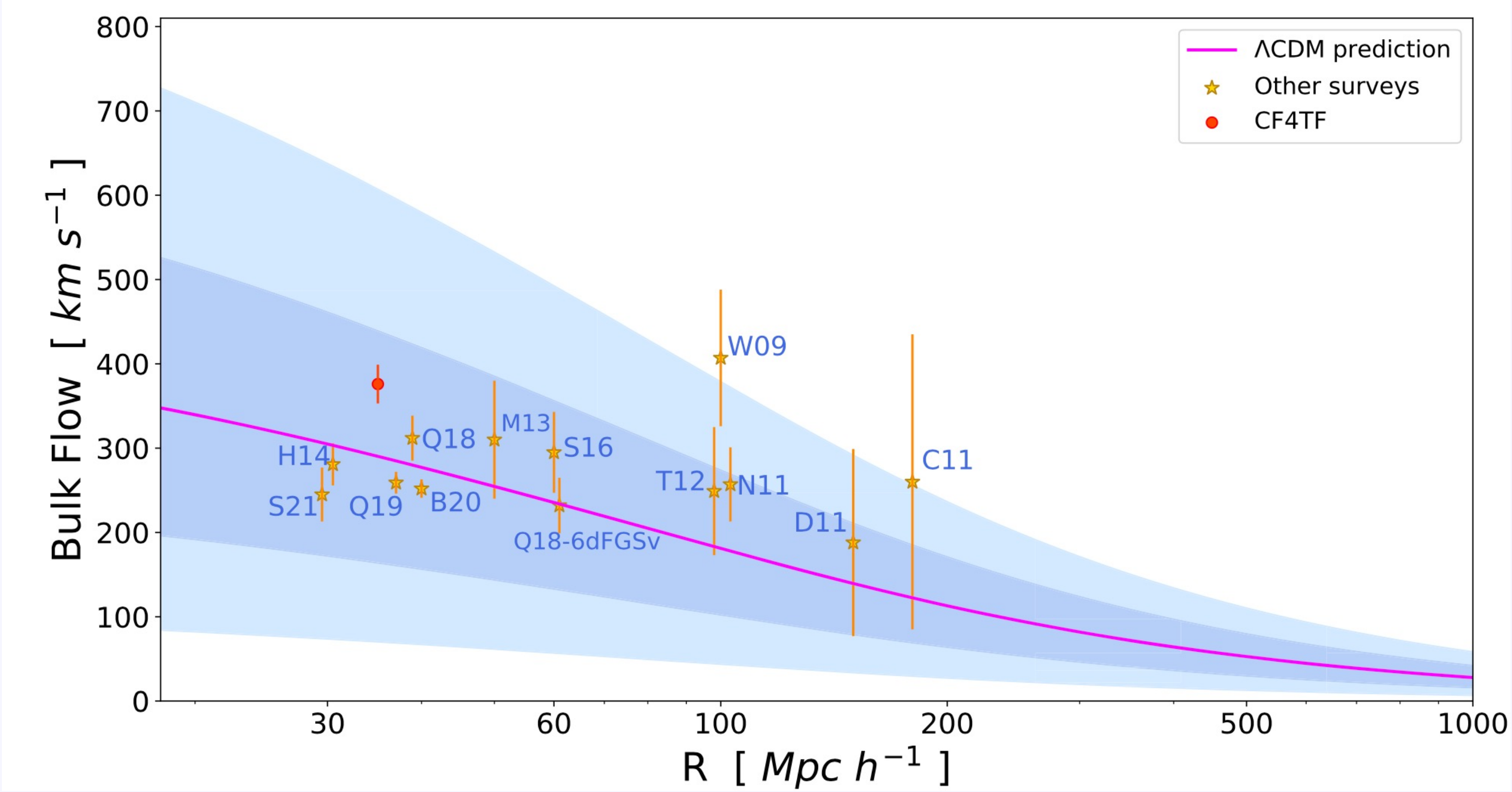


George Smoot, Nobel Lecture, 8 Dec 2006

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

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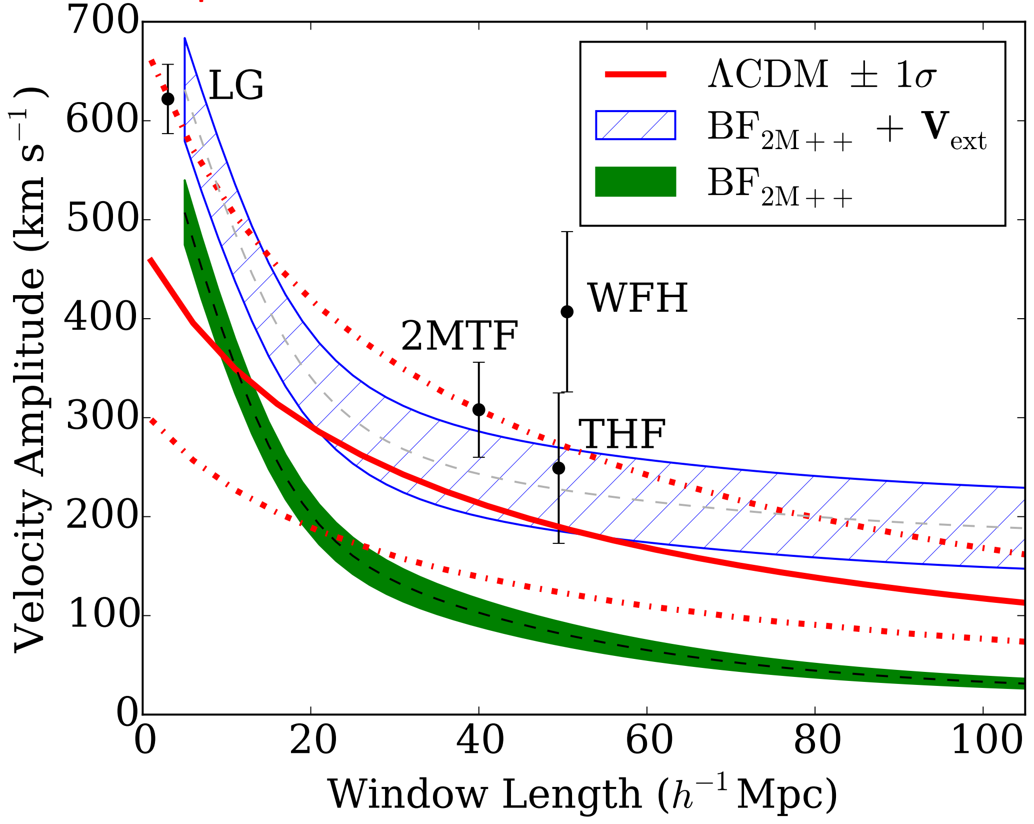
ABSTRACT

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_{100}^{-1} Mpc.

Key words. Cosmology: large-scale structure of Universe

Where is the cosmic ‘rest frame’?

This is the model using which Pantheon and Pantheon+ compilations correct for peculiar velocities

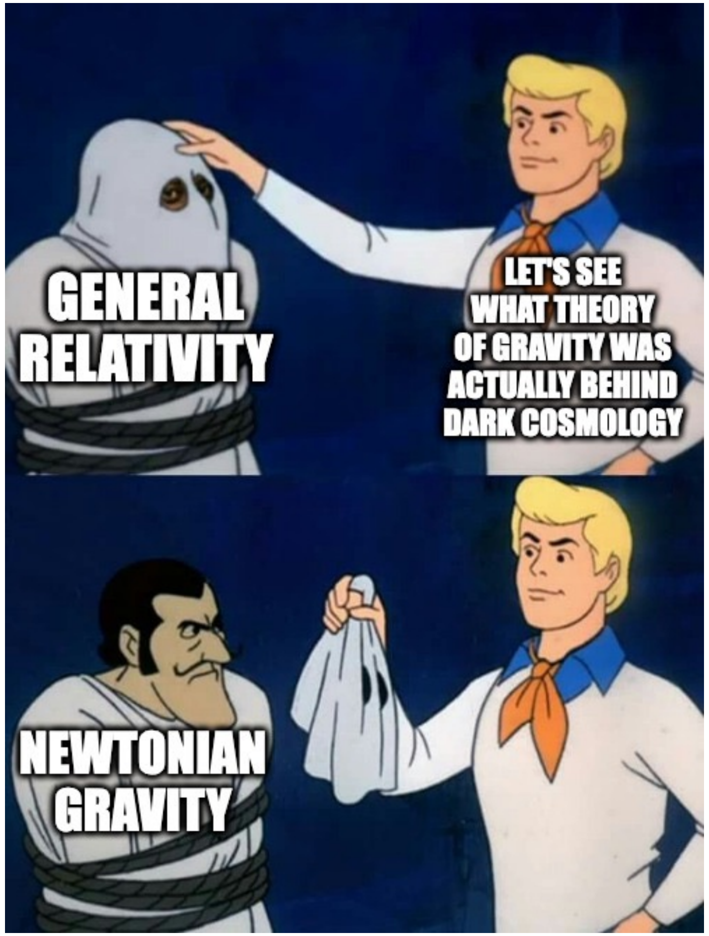


Carrick, Turnbull, Lavaux, Hudson *MNRAS*, 450, 1, 11 2015, 317–332

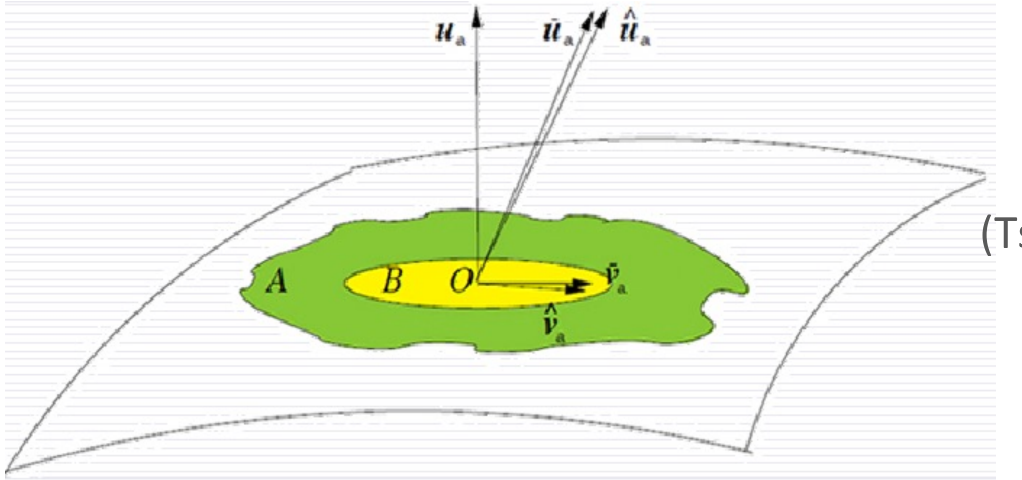
“We find that an external bulk flow is preferred at the 5.1σ level, and the best fit has a velocity of 159 ± 23 km s^{-1} towards *l* = 304° ± 11°, *b* = 6° ± 13°” [beyond 200 h^{-1} Mpc radius]

Infers the peculiar velocity field from a density contrast field derived from data – 2M++ compilation, using linear Newtonian perturbation theory.

$$v(\boldsymbol{r}) = \frac{H_0 f(\Omega_m)}{4\pi b_g} \int \delta_g(\boldsymbol{r}') \frac{(\boldsymbol{r}' - \boldsymbol{r})}{|\boldsymbol{r}' - \boldsymbol{r}|^3} d^3\boldsymbol{r}'.$$

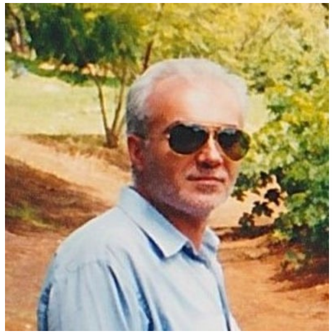


The tilted Friedmann Universe



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

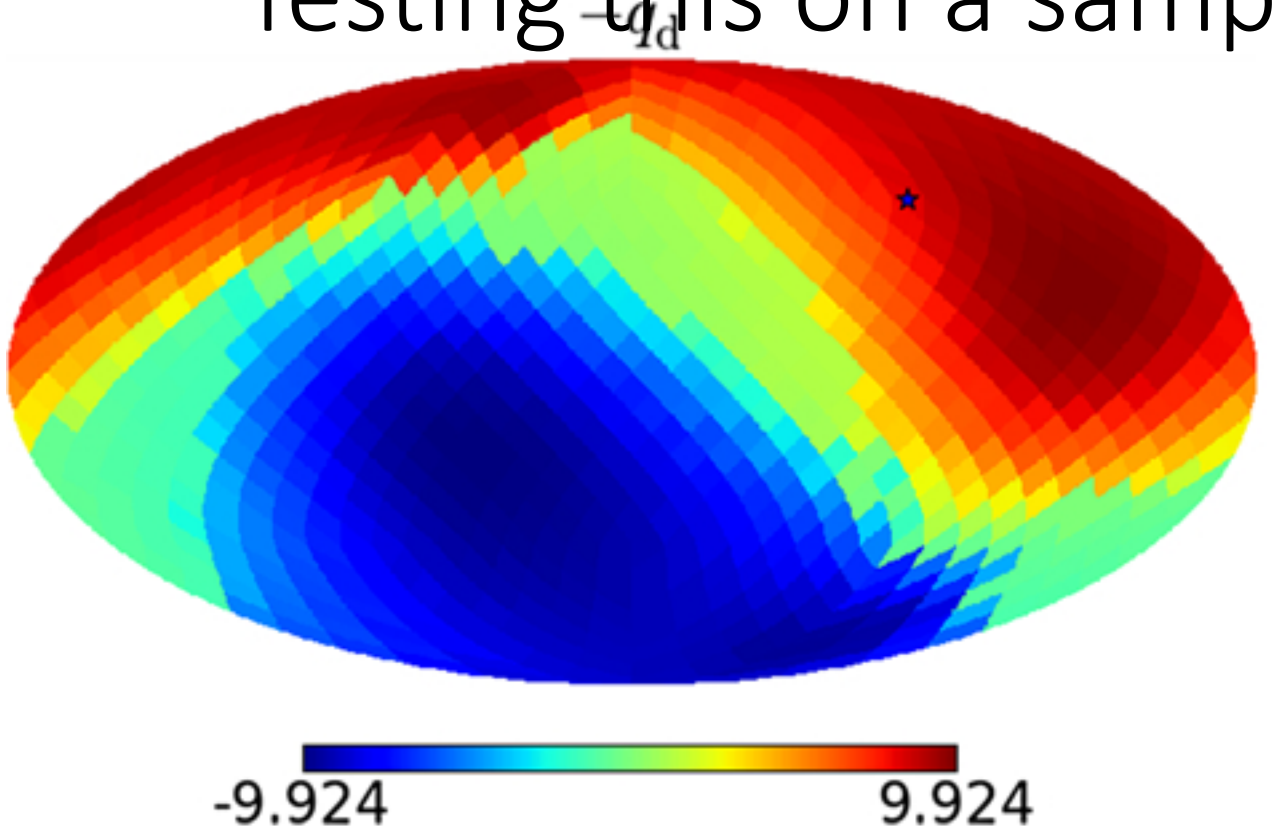
$$\tilde{\Theta} = \Theta + \vartheta,$$

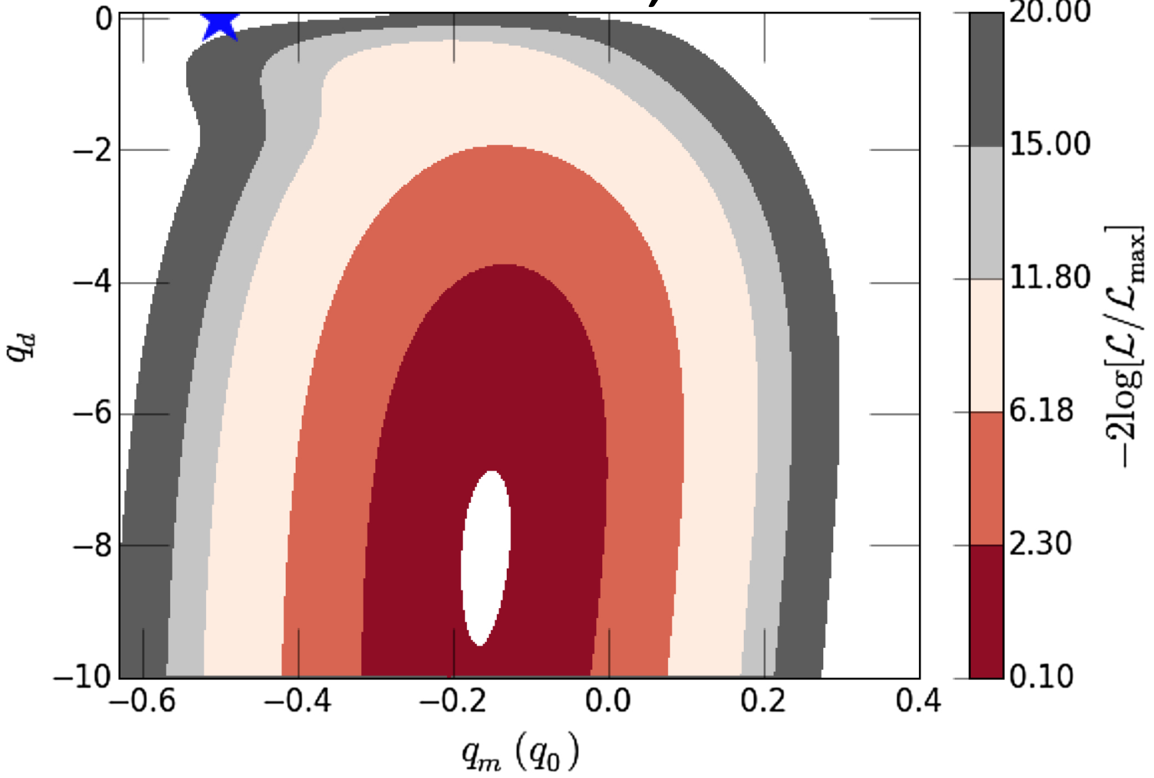
$$1 + \tilde{q} = (1+q)\left(1 + \frac{\vartheta}{\Theta}\right)^{-2} - \frac{3\dot{\vartheta}}{\Theta^2}\left(1 + \frac{\vartheta}{\Theta}\right)^{-2},$$

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.**

Testing this on a sample of 740 SN1e, JLA





https://github.com/rameez3333/Dipole_JLA

The dipolar component of q is larger than the monopole, and dominates out to z>0.1, closely aligned to the CMB dipole

The significance of q_o being negative is $<1.4\sigma$!

Dipole Statistically significant at $3.9\ \sigma$ level

In agreement with the predictions by Tsagas,

Kicked off a debate with mainstream supernova cosmologists, about the data being corrected for 'peculiar velocities'

Cosmic acceleration may simply be an artefact of our being located inside a 'bulk flow'!

The question of peculiar velocity ‘corrections’

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

$$d_L(z) = \bar{d}_L(\bar{z})\,\left(1 + z_{pec}^{hel}\right)\left(1 + z_{pec}^{SN}\right)^2$$

Davis et. al. Astrophys.J. 741 (2011) 67
Ellis & Stoeger 1987

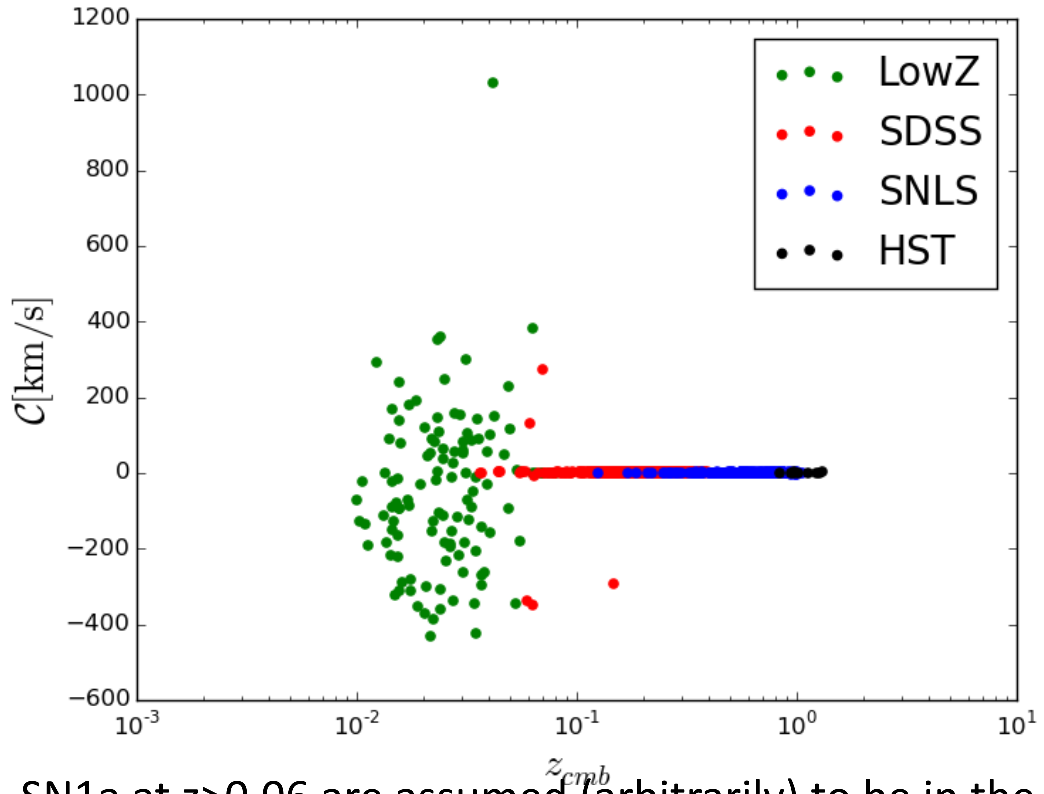
JLA (and Pantheon) redshifts and magnitudes have been ‘corrected’ to account for the local bulk flow.

```
#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
```

$z_{hel} \rightarrow measured$

$z_{cmb} \rightarrow inferred\ using\ a\ flow\ model$

$$C = [(1 + z_{hel}) - (1 + z_{cmb})(1 + z_d)] \times c$$



SN1a at z>0.06 are assumed (arbitrarily) to be in the CMB rest frame. (only uncorrelated 150 km/s in error budget)

Flow model – SMAC has a ~600 km/s residual bulk flow

Consequently, we use only z_{hel} and subtract out the corrections to m_B

The Dipole of the Pantheon+SH0ES Data

Francesco Sorrenti, Ruth Durrer and Martin Kunz

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Université de Genève, 24 quai Ernest Ansermet, 1211 Genève 4, Switzerland

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Abstract. In this paper we determine the dipole in the Pantheon+ data. We find that, while its amplitude roughly agrees with the dipole found in the cosmic microwave background which is attributed to the motion of the solar system with respect to the cosmic rest frame, the direction is different at very high significance. While the amplitude depends on the lower redshift cutoff, the direction is quite stable. For redshift cuts of order $z_{\rm cut} \simeq 0.05$ and higher, the dipole is no longer detected with high statistical significant. An important rôle seems to be played by the redshift corrections for peculiar velocities.

4.4 The peculiar velocities in the Pantheon+ analysis

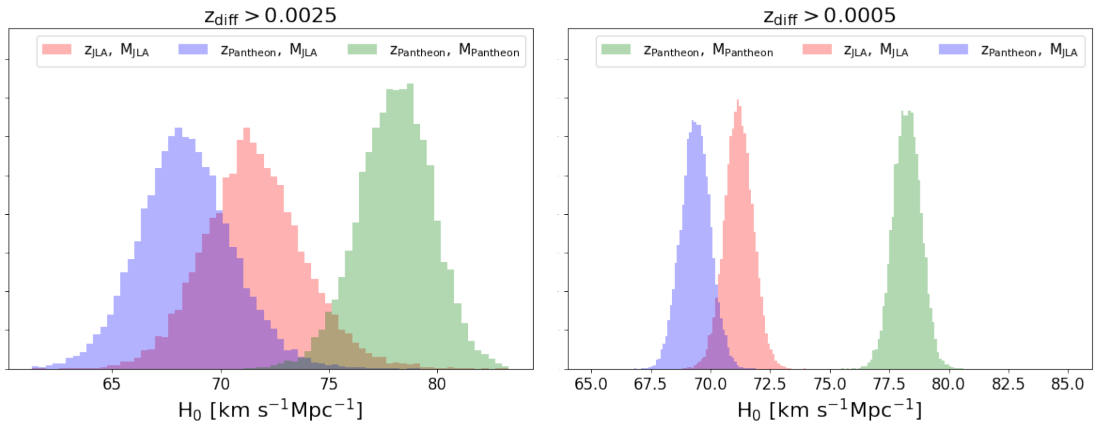
An important difference between our treatment and the Pantheon+ analysis [18], lies in the peculiar velocities of the SNe which we neglect in our analysis. The main reason we do this is that they should not contribute significantly to the dipole which is the main aim of this work. We also consider it problematic that the peculiar velocities inferred in [18] come purely from linear gravitational infall [24, 29], even though it is known from numerical simulations that at late times vorticity is as relevant as (if not larger than) the

No Hubble tension either

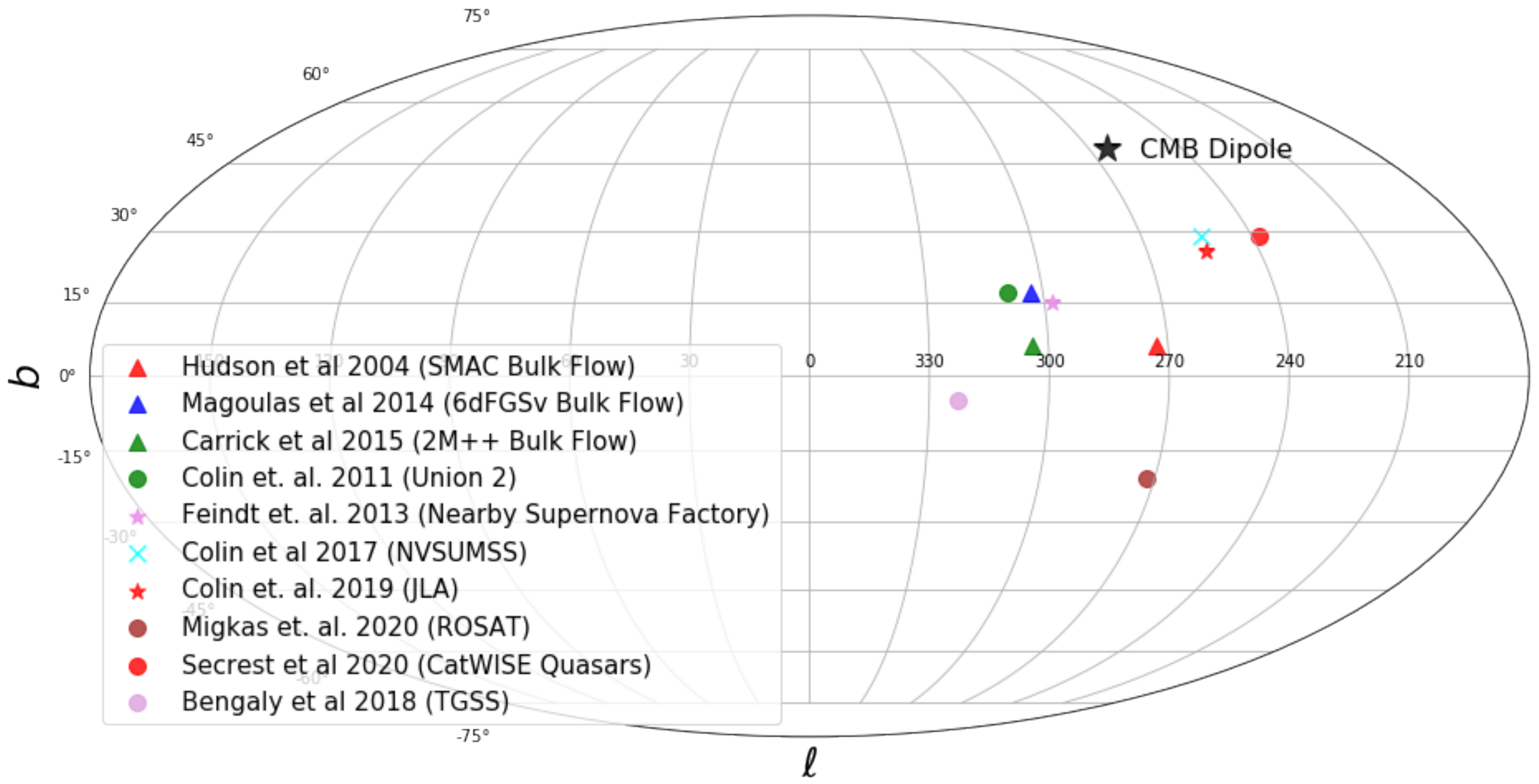
New Constraints on Anisotropic Expansion from Supernovae Type Ia

W. Rahman[1★], R. Trotta[1,2,3], S. S. Boruah[4], M. J. Hudson[5,6,7], and D. A. van Dyk[2,8]

The model used in Betoule et al. (2014) to estimate $z_{\rm pec}^{\rm SN}$ has been criticised by C19, who highlighted potential bulk flow velocity discontinuities at $z = 0.04$, pointed out that peculiar velocity corrections arbitrarily disappear beyond $200/h$ Mpc ($z \sim 0.067$, the limit of the galaxy density field measurements from which the peculiar velocities were derived) and that the residual uncorrelated velocity dispersion of $\sigma_v = 150$ km/s might be underestimated. While RH20 pointed out technical flaws with the analysis of C19, it is important in the light of this valid criticism to revisit the issue of low-redshift peculiar velocity corrections here.



Class.Quant.Grav. 38 (2021) 15, 154005


CMB Dipole
Hudson et al 2004 (SMAC Bulk Flow)
Magoulas et al 2014 (6dFGSv Bulk Flow)
Carrick et al 2015 (2M++ Bulk Flow)
Colin et. al. 2011 (Union 2)
Feindt et. al. 2013 (Nearby Supernova Factory)
Colin et al 2017 (NVSUMSS)
Colin et. al. 2019 (JLA)
Migkas et. al. 2020 (ROSAT)
Secrest et al 2020 (CatWISE Quasars)
Bengaly et al 2018 (TGSS)
b
ℓ
75°
60°
45°
30°
15°
0°
-15°
-30°
-45°
-60°
-75°
30
0
330
300
270
240
210

Conclusion

The Universe is anisotropic and the Cosmic Rest frame does not exist

- Ellis & Baldwin tests performed on Radio galaxy catalogues and WISE 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 has been falsified.
- SN1a data are better fit by a "tilted Friedmann model". Ensuing debate stultifies dark energy evidence.
- Strong hint towards the inhomogeneous cosmological models.
- Highlighted by Peebles in his review of anomalies in physical cosmology.
- 300+ citations, Quanta Magazine, New Scientist
- Stultifies the Hubble tension:
  - *M.R. and Subir Sarkar, Class.Quant.Grav.* 38 (2021) 15, 154005

A new cosmological tension!

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

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

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 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)

This talk:

- Is the CMB dipole really ‘purely kinematic’? Dipoles in number counts of flux limited catalogues:
  - High redshift Radio Galaxies (NVSS + SUMSS) **MNRAS 471 (2017) no.1, 1045-1055**
  - Low redshift infrared galaxies (AllWISE) **MNRAS 477 (2018) no.2, 1772-1781**
  - High Redshift Quasars (CatWISE) arXiv: 2009.14826
  - Gaia UnWISE in preparation

The situation that Ellis & Baldwin anticipated in 1984 has arrived.

- The bulk flow of the local Universe. Where is the cosmic rest frame?

- The tilted Friedmann Universe.
  - “Evidence for anisotropy of Cosmic Acceleration” : **A&A 631, L13 (2019)**

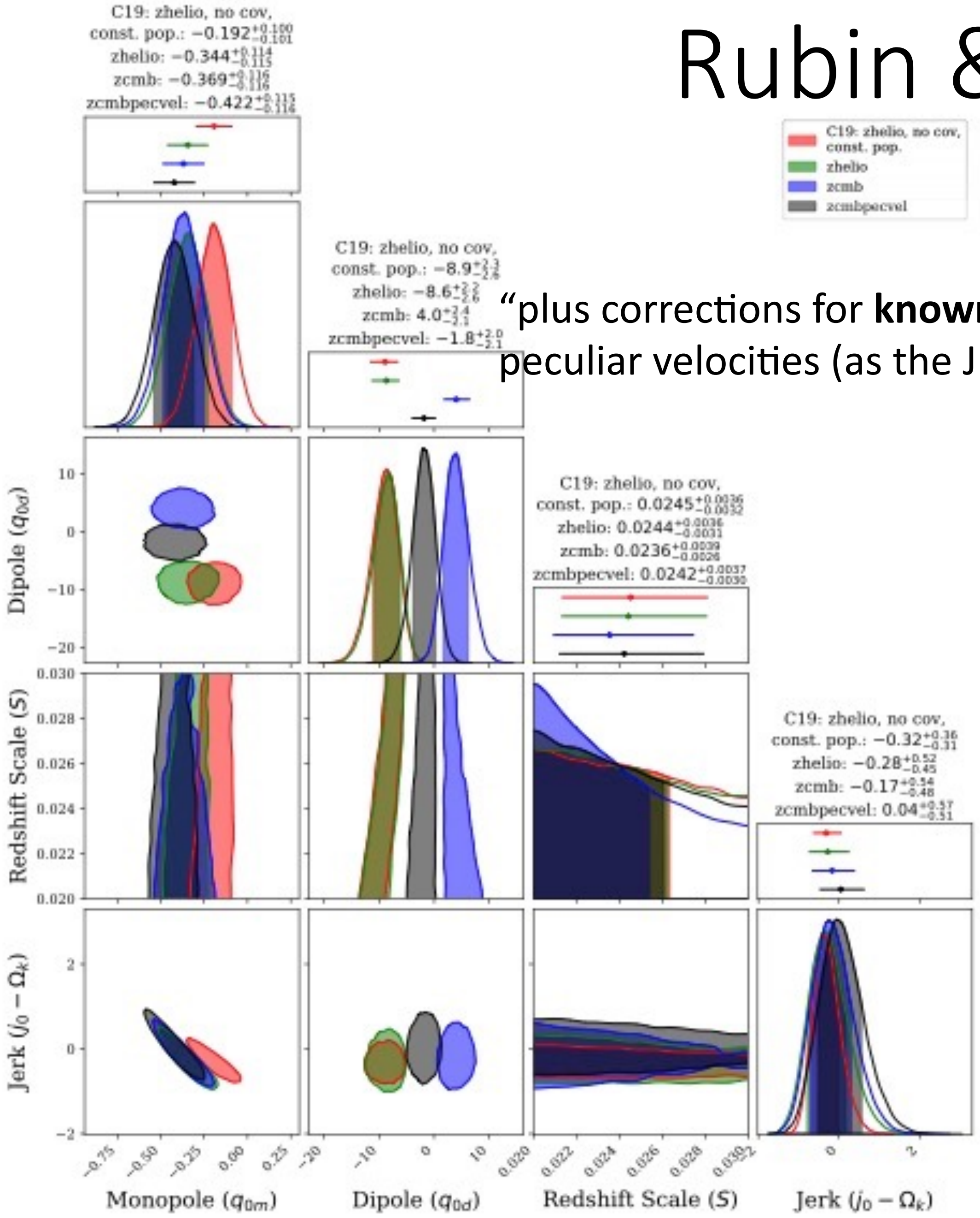
    An amusing debate: arXiv:1912.04257

The issue of peculiar velocities and corrections.

- The Hubble tension makes no sense arXiv : 1911.06456
- What exactly is going on in cosmology now.
- Backup

  A historical review of Supernova cosmology and fitting.

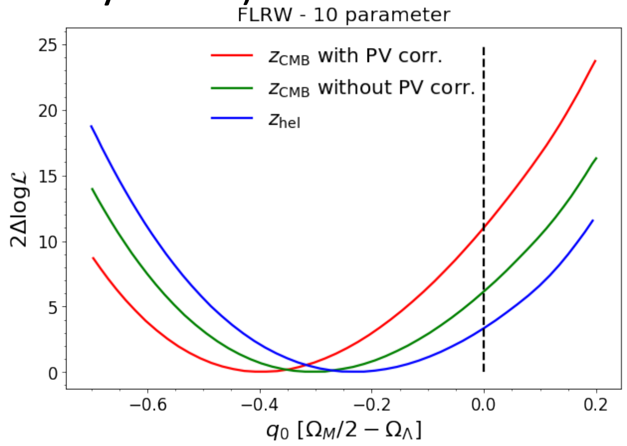
Rubin & Heitlauf 2019

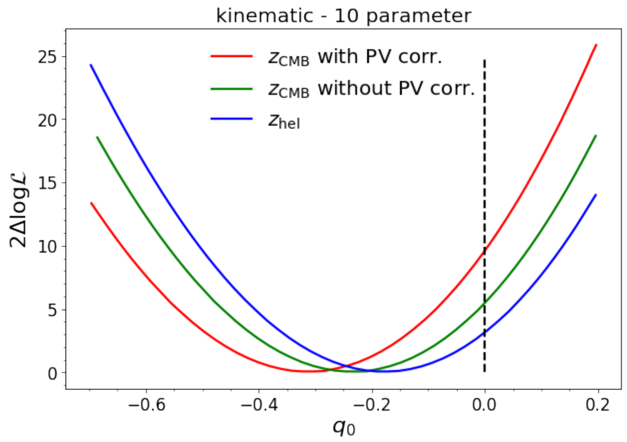


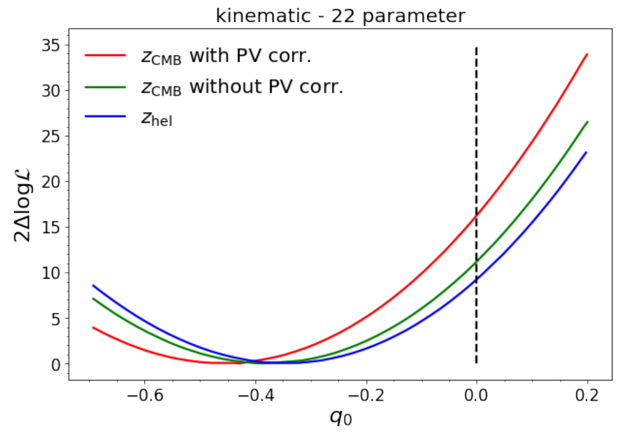
$$\Delta\mu_{pv} = \frac{5}{\log(10)} \frac{v}{zc}$$

"plus corrections for **known** peculiar velocities (as the JLA analysis did)"

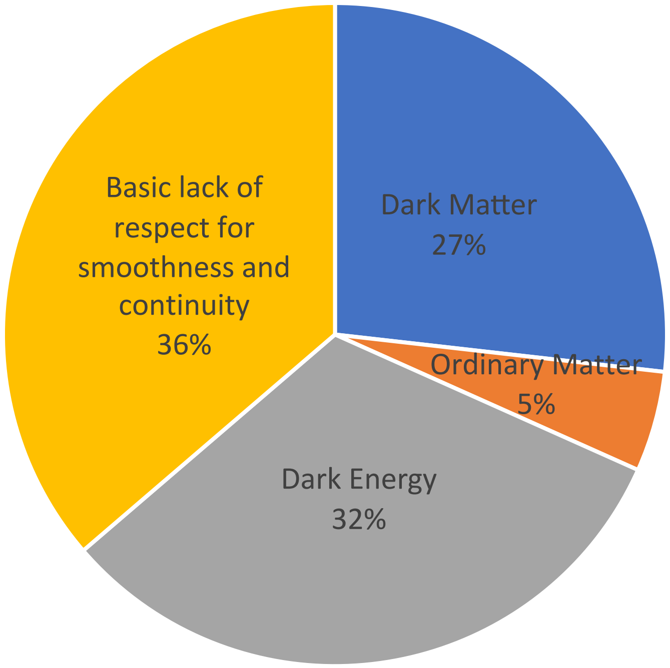
Our Response







About ~half the evidence (relative dimming of high z SNe has to be put into the data) !!


Basic lack of respect for smoothness and continuity
36%
Dark Matter
27%
Ordinary Matter
5%
Dark Energy
32%

Peculiar velocity impact on SN1a magnitude

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

$$d_L(z) = \bar{d}_L(\bar{z})\ \left(1 + z_{pec}^{hel}\right)\left(1 + z_{pec}^{SN}\right)^2$$

Davis et. al. Astrophys.J. 741 (2011) 67

JLA (and Pantheon) redshifts and magnitudes have been ‘corrected’ to account for the local bulk flow.

```
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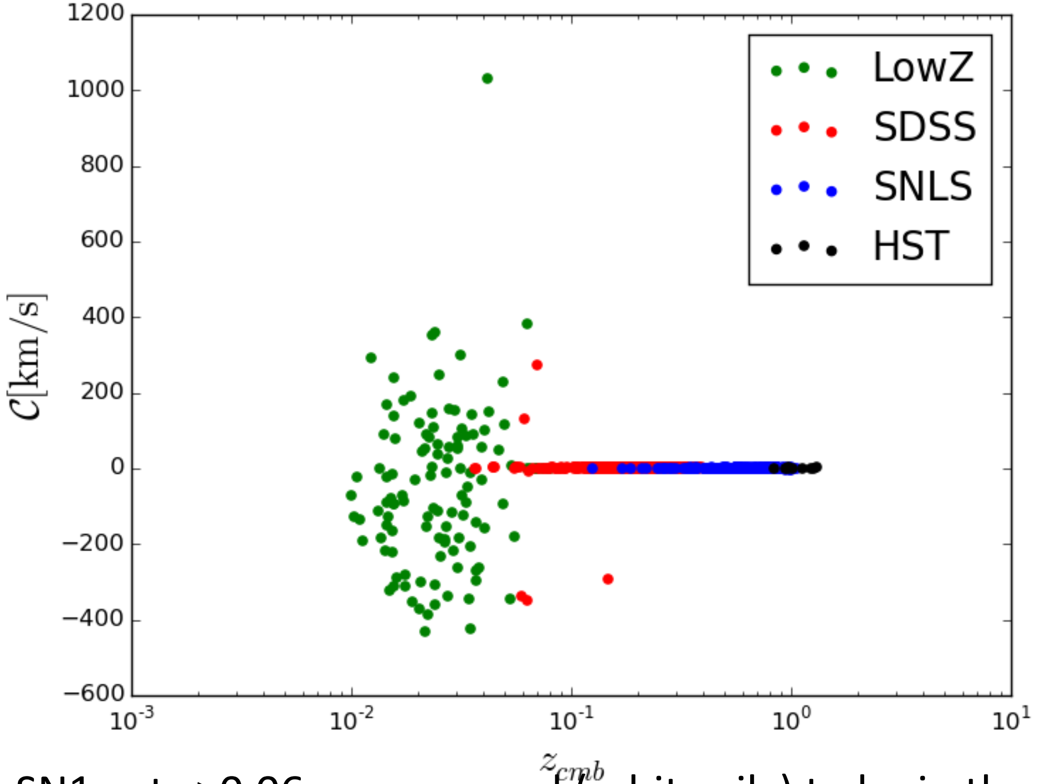
$z_{cmb} \rightarrow inferred\ using\ a\ flow\ model$

$$C = [(1 + z_{hel}) - (1 + z_{cmb})(1 + z_d)] \times c$$



SN1a at z>0.06 are assumed (arbitrarily) to be in the CMB rest frame. (only uncorrelated 150 km/s in error budget)

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Consequently, we use only z_{hel} and subtract out the corrections to m_B

Peculiar velocity impact on SN1a magnitude

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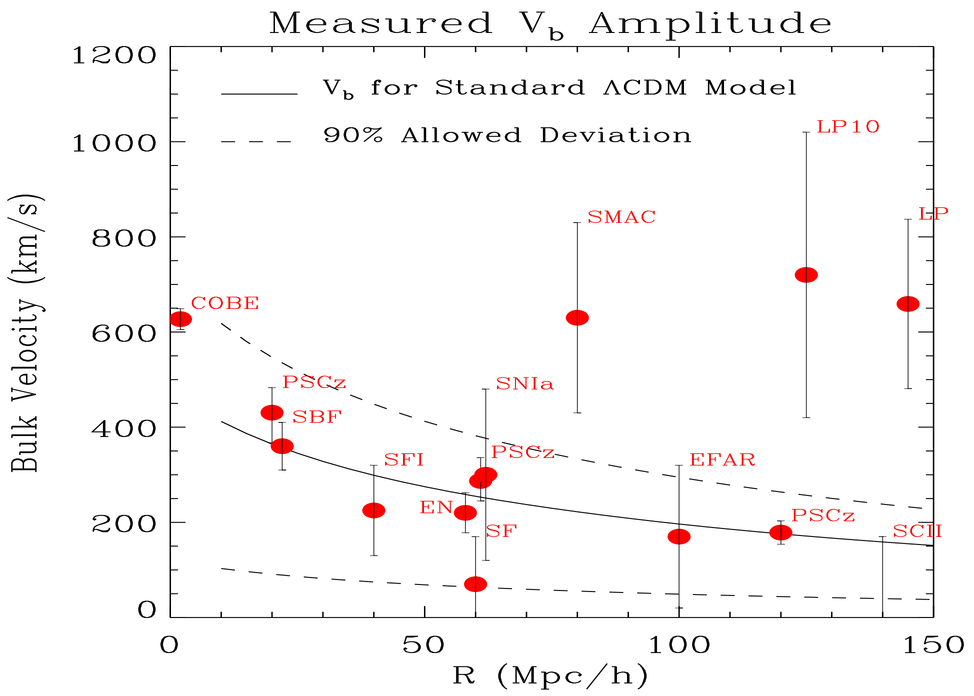
$$d_L(z) = \bar{d}_L(\bar{z})\,(1 + z_{pec}^{hel})(1 + z_{pec}^{SN})^2$$

Davis et. al. Astrophys.J. 741 (2011) 67

$$C = [(1 + z_{hel}) - (1 + z_{cmb})(1 + z_d)] \times c$$



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03D1bp 0.345928 0.347000 0 22.398137 0.087263
03D1co 0.677662 0.679000 0 24.078115 0.098356
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03D1fc 0.330932 0.332000 0 21.861412 0.086437
03D1fq 0.798566 0.800000 0 24.510389 0.101777
```

SN1a at z>0.06 are assumed (arbitrarily) to be in the CMB rest frame. (only uncorrelated 150 km/s in error budget)
Wrong ‘correction’ to SDSS2308 in JLA. Many such mistakes in Pantheon (eg : SN2246).
Flow model – SMAC has a ~600 km/s residual bulk flow

$z_{hel} \rightarrow measured$
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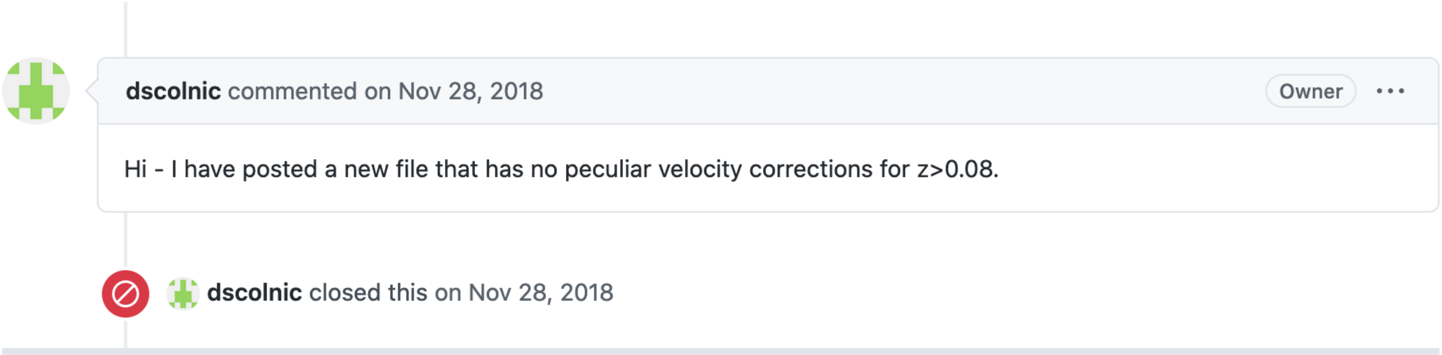
Consequently, we use only z_{hel} and subtract out the corrections to m_B

There is an arbitrary discontinuity within the data.

Also in the subsequent Pantheon compilation


dscolnic commented on Nov 28, 2018 Owner

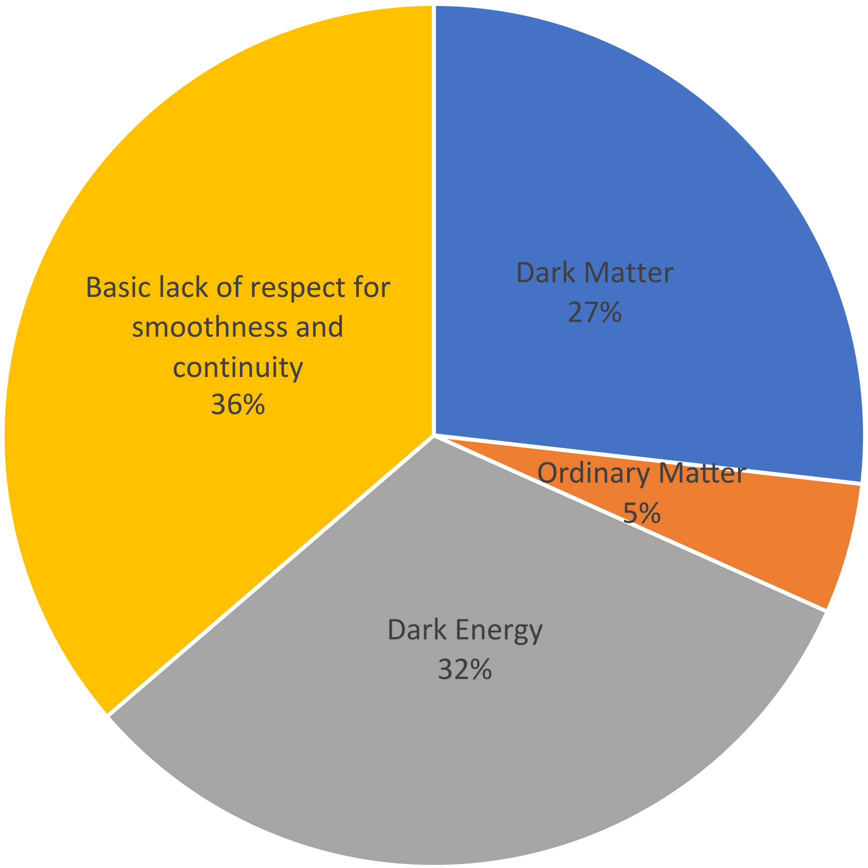
Hi - I have posted a new file that has no peculiar velocity corrections for z>0.08.

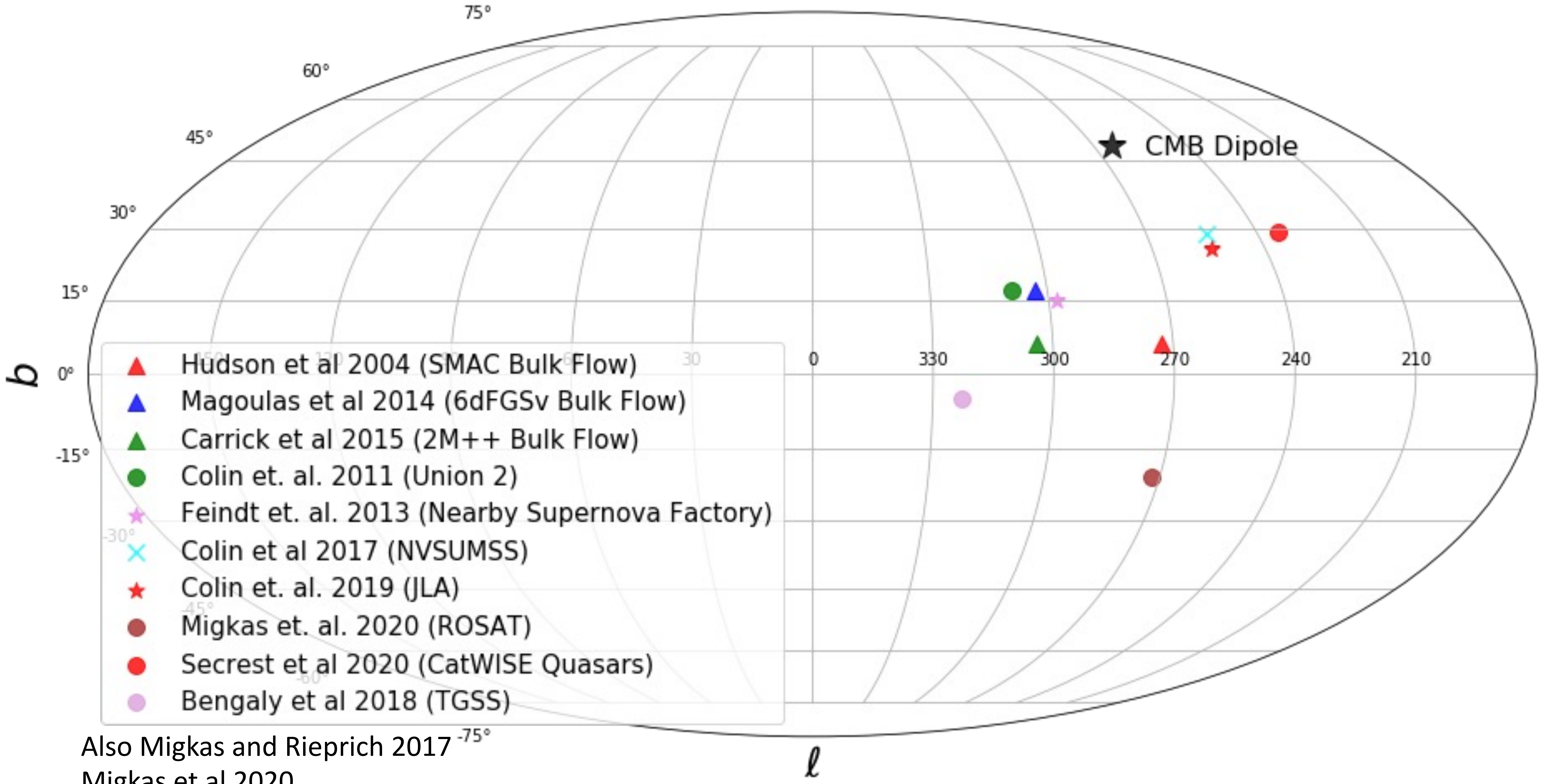
dscolnic closed this on Nov 28, 2018

https://github.com/dscolnic/Pantheon/issues/2

This is because in the absence of demonstrable convergence between the bulk flow of the local Universe and the 'CMB rest frame', there is no way to correct for it completely (one could fit it as a nuisance parameter).

Key Hubble tension papers rely on these corrections or directly on the Pantheon compilation (for eg Kenworthy et al 2019)





Also Migkas and Rieprich 2017
Migkas et al 2020.

What we mean by ‘non Copernican observers’

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

The FLRW universe

Can be described by one scale factor a(t) and Friedmann equations exactly.

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

The cosmic sum rule

Maximal symmetry forbids peculiar velocities

The Real Universe

$$\dot{\Theta} = -\frac{\theta^2}{3} - 2\sigma^2 + 2\omega^2 - E\left[\vec{X}\right]^a{}_a + \dot{X}^a{}_{;a} + \Lambda$$

Ellis, “On the Raychaudhury Equation”
Pramana–J.Phys.,Vol. 69, No. 1, July 2007

Everything has a peculiar velocity of ~10^{-3}, they should be viewed as differences in the expansion rate of the Universe

Some existing debates in literature (inhomogeneous cosmology/backreactions) suggest that problems such as Dark Matter and Dark Energy can also be tackled be critically examining the tools and framework with which we do cosmology.

What we mean by ‘non Copernican observers’

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

The Real Universe

Table 1: Comparison of curvature properties within the FLRW class of cosmological models and for generic averaged globally hyperbolic spacetime models.

Buchert and Heinesen 2020

	FLRW	Average within generic GR
Topology	sign($\mathcal{R}$) determines the spatial topology for simply-connected domains	$\langle\mathcal{R}\rangle_{\mathcal{D}}$ does not in general allow conclusions on topological properties
Integral constraint	local ‘Newtonian’ energy conservation: $(\,\mathcal{R}a^2\,)^{\cdot} = 0$	general-relativistic coupling of $\langle\mathcal{R}\rangle_{\mathcal{D}}$ to structure: $\frac{1}{a_{\mathcal{D}}^6}\,(\,\mathcal{Q}_{\mathcal{D}}\;a_{\mathcal{D}}^6\,)^{\cdot} + \frac{1}{a_{\mathcal{D}}^2}\,(\,\langle\mathcal{R}\rangle_{\mathcal{D}}\,a_{\mathcal{D}}^2\,)^{\cdot} = 0$
Sign of curvature	sign($\mathcal{R}$) is preserved throughout the evolution of the Universe and on all scales	sign($\langle\mathcal{R}\rangle_{\mathcal{D}}$) can change in response to structure in the spacetime and may vary on different scales
Copernican principle	satisfied in its most strict interpretation. All fundamental observers are subject to the same local curvature	can be satisfied in a weaker sense than for FLRW. ‘Distributional equivalence’ between observers

Can be de

Friedman

$\dot{X}^a{}_{;a} + \Lambda$

hury Equation”

o. 1, July 2007

Maximal

hould be

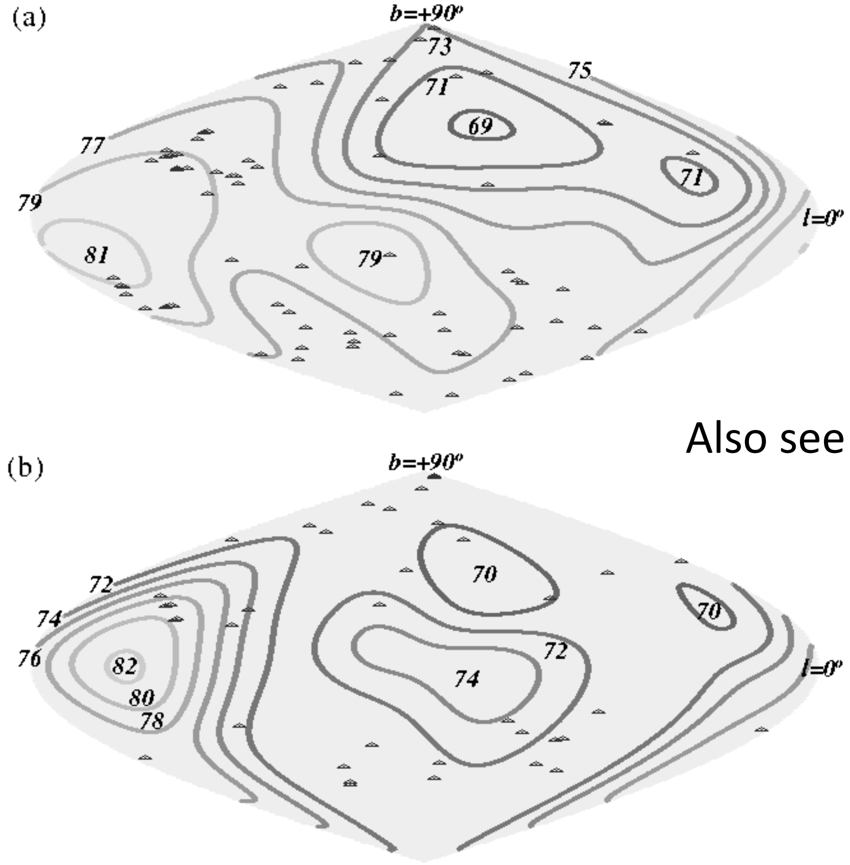
Universe

ms

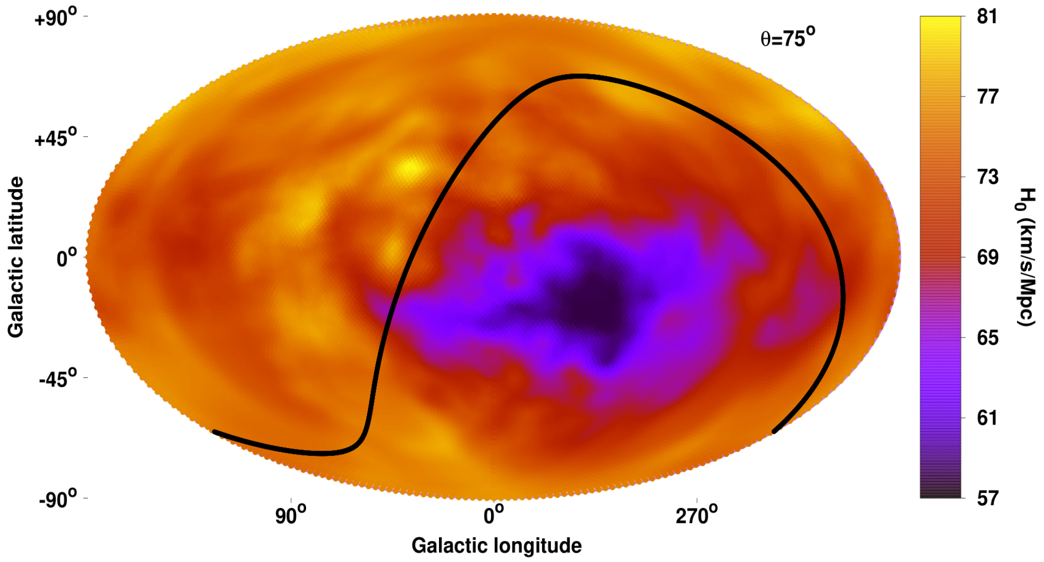
such as Dark Matter and Dark Energy can also be tackled be critically examining the tools and framework with which we do cosmology.

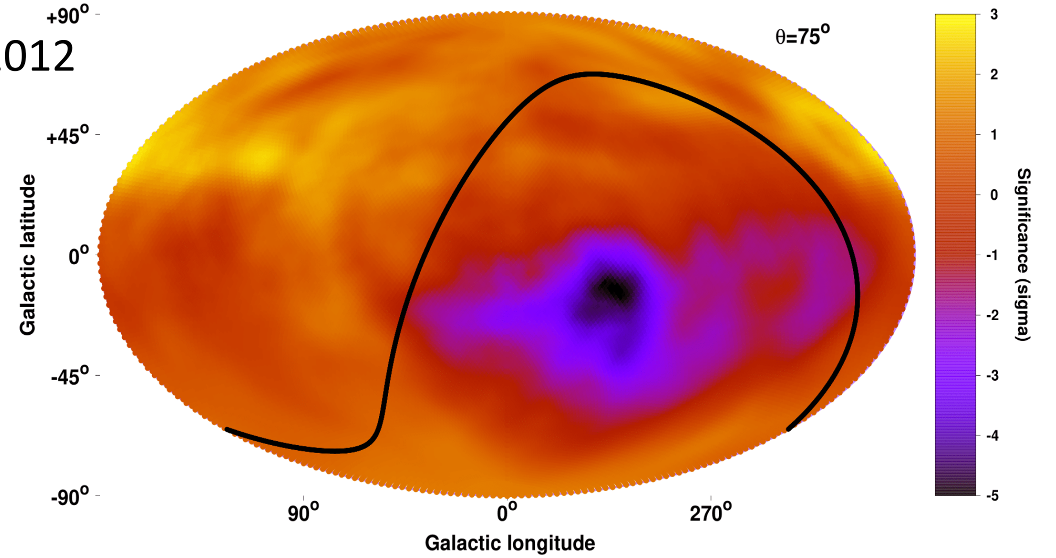
There is no Hubble constant, let alone a tension

McClure and Dyer 2007, motivated
by the Raychoudhury Equation



Also see Wiltshire et al 2012





A statistically significant difference in expansion rate of 9 km s^{-1} Mpc^{-1} is found to occur across the sky.

Migkas et al 2020

Conclusions

- Number counts of flux limited catalogues in radio and infrared all indicate somewhat significant (up to $\sim 3.9\sigma$) tensions with the 'purely kinematic' interpretation of the CMB dipole.
  - Hopeful that SKA and EUCLID can set this to rest by testing.
- Convergence to the CMB rest frame has not been demonstrated.
  - There is a case for precision testing the CMB dipole.
  - The local Universe has a bulk flow out to ~400 Mpc.

    McClure and Dyer 2007

    The CMB rest frame does not exist

- SN1a data pre ship with 'corrections' and are being continuously adjusted. The Hubble tension is manufactured using these corrections.

- Evidence $3.9\ \sigma$ for a tilt in the local Universe. Isotropic acceleration compatible with 0 at < 1.4 sigma

- Since ΛCDM cosmology is dying, time to move to an anisotropic cosmology.