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

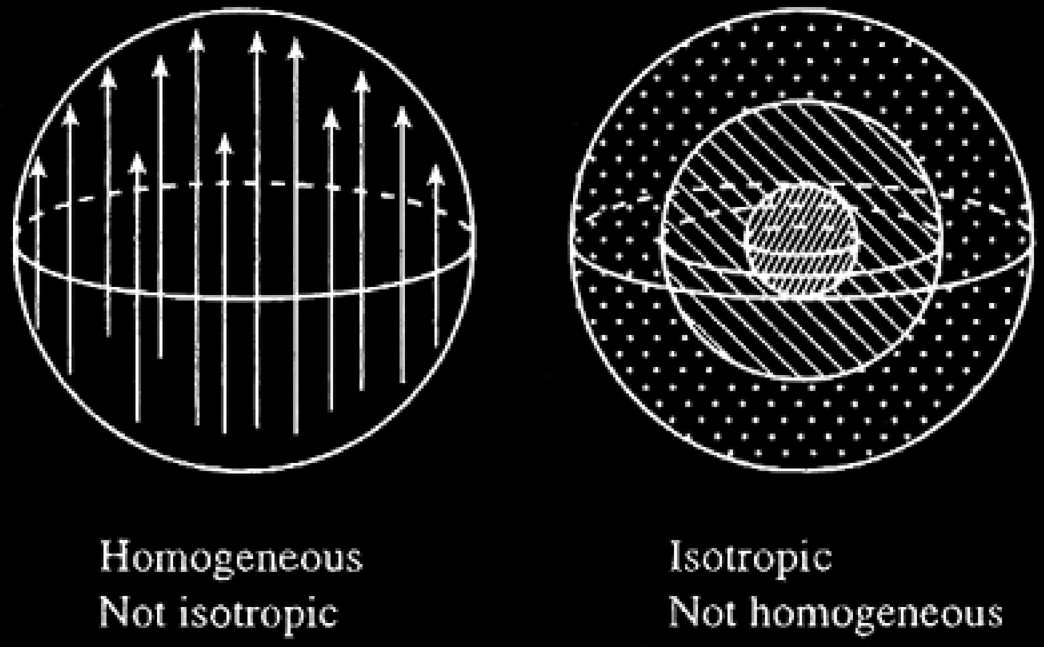
PPC 2024

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

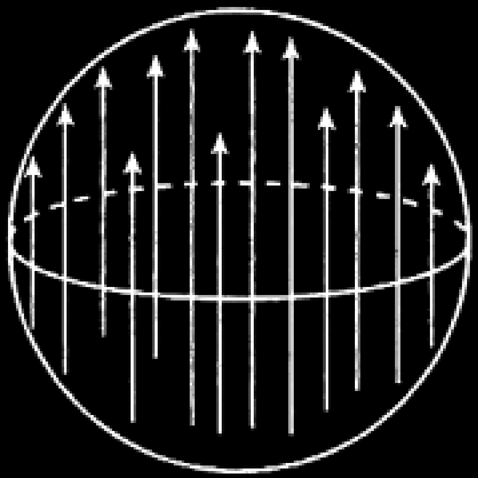
Scale factor a(t)

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

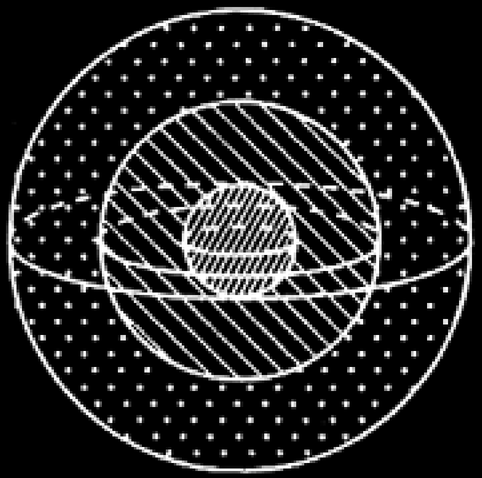
The cosmic sum rule

The cosmological principle

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



Homogeneous
Not isotropic



Isotropic
Not homogeneous

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"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. …

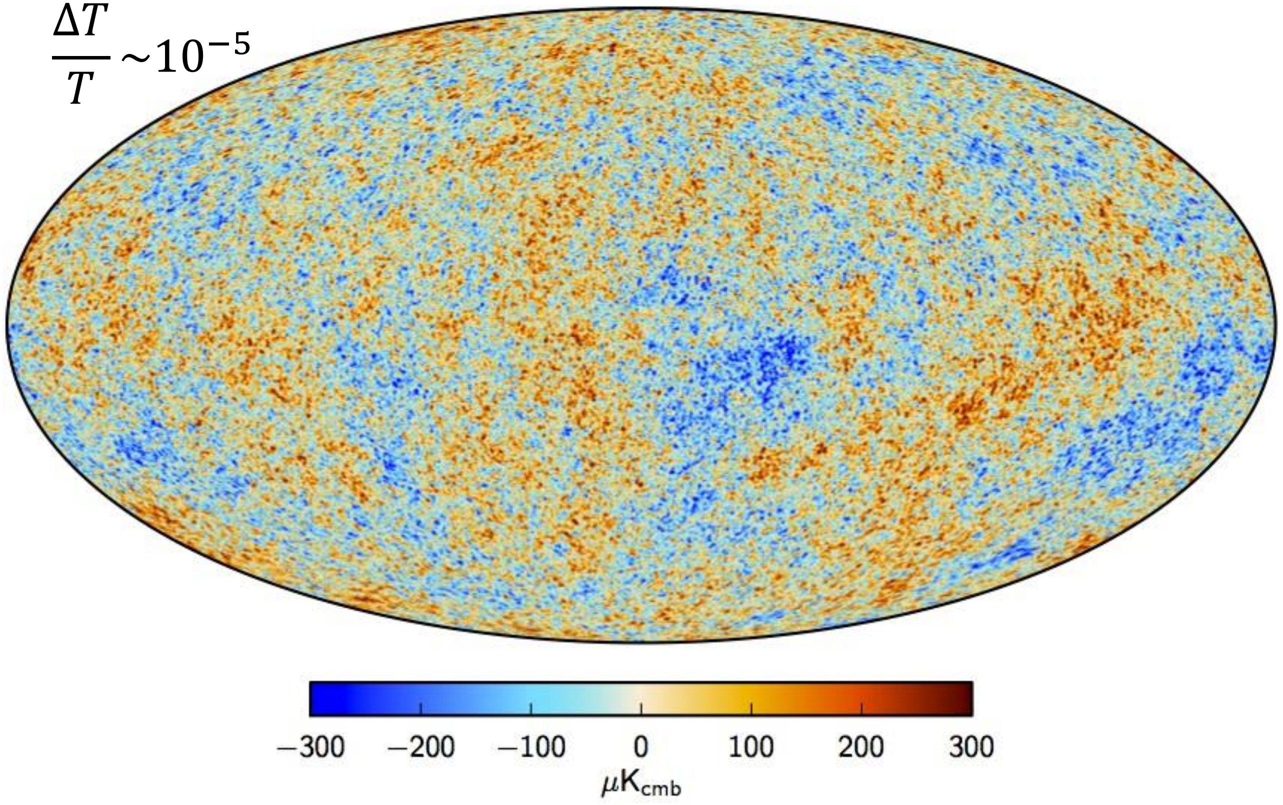
… If the data will not fit into this framework, we shall be able to conclude that either the Cosmological Principle or the Principle of Equivalence is wrong. Nothing could be more interesting.

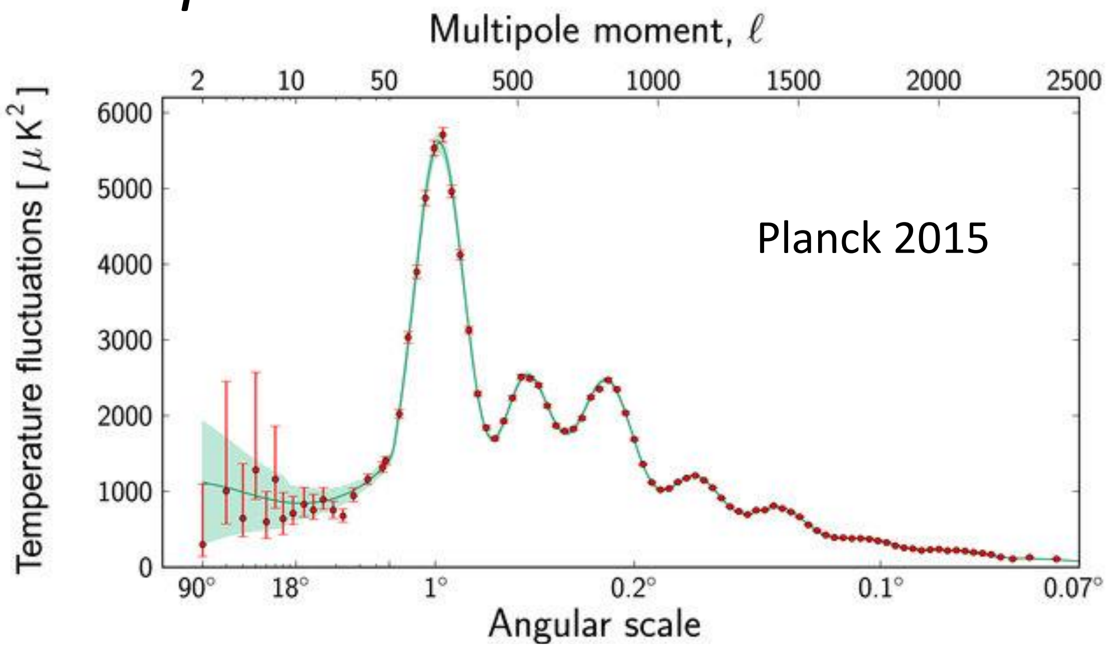
Steven Weinberg, *Gravitation and Cosmology* (1972)

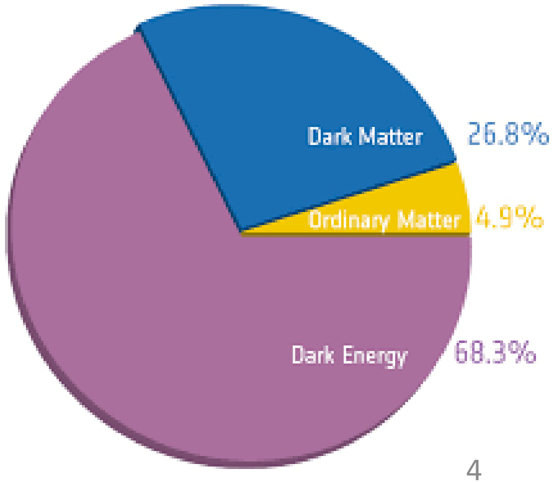
"Data from the Planck satellite show the Universe to be highly isotropic"

T = 2.725 K

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

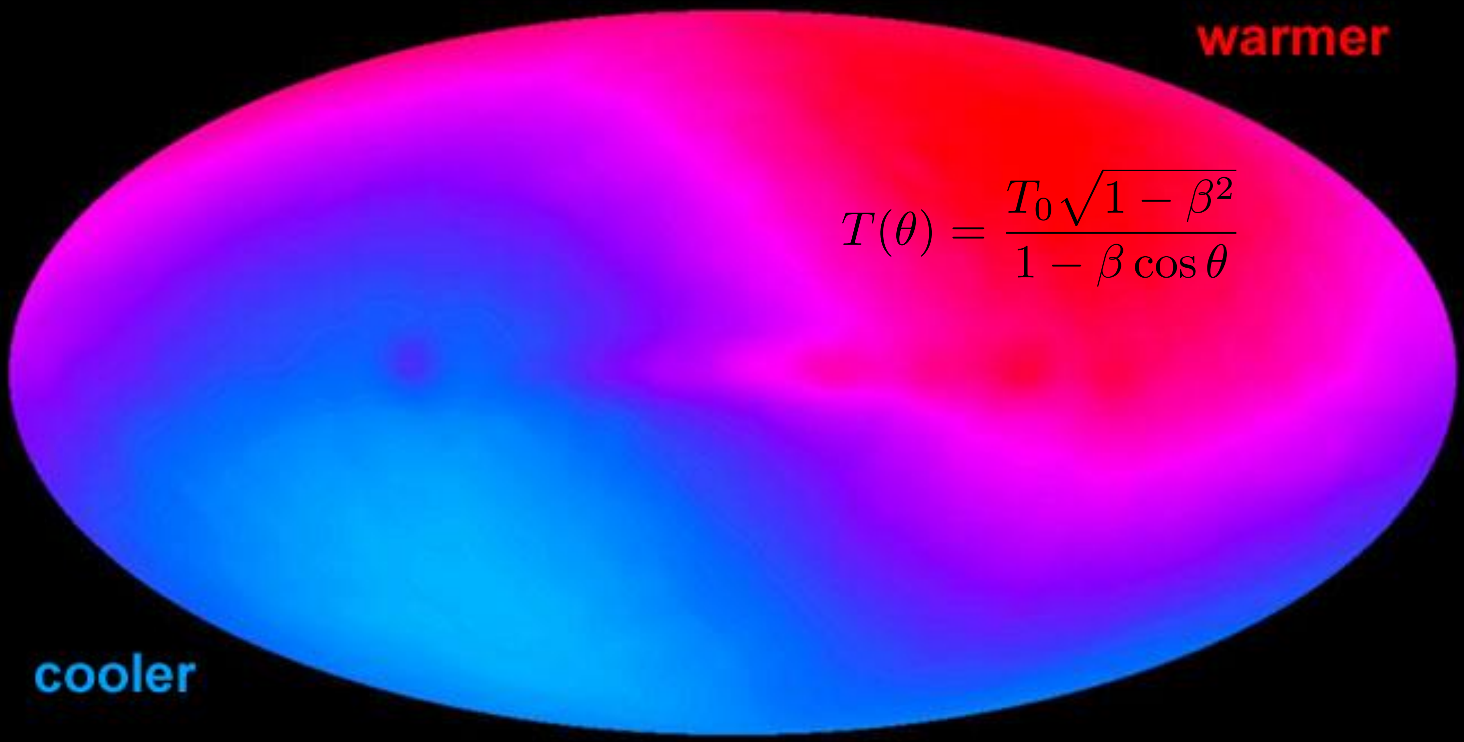






We observe a statistically isotropic Gaussian random field of small temperature fluctuations (fully quantified by the 2-point correlations ➛ angular power spectrum)

The CMB Dipole : Purely Kinematic?



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

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?

COBE Experiment, 1996
Planck 2015

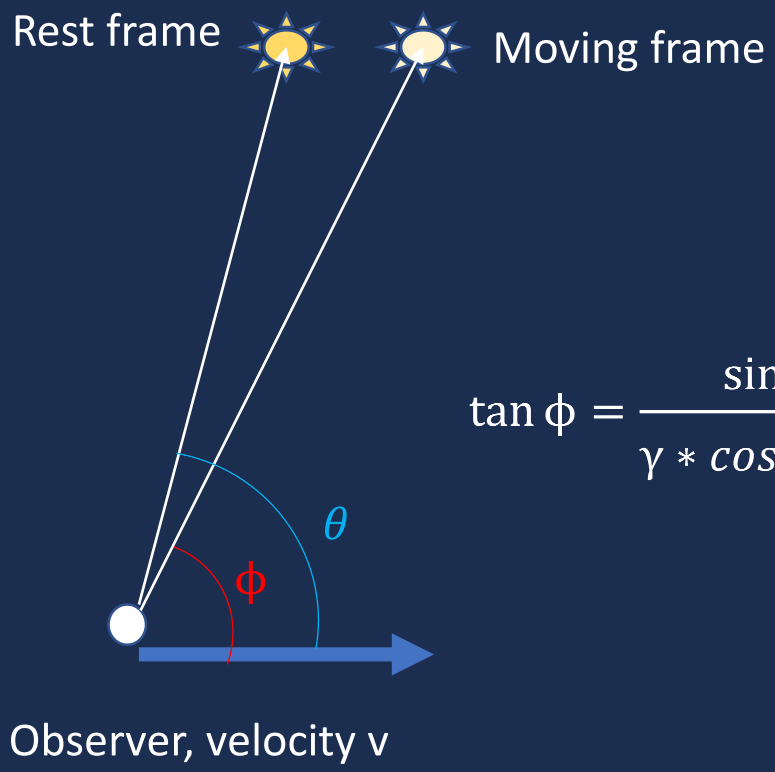
$$\frac{\Delta T}{T} \sim 10^{-3}$$

A moving observer - Kinematic Dipole

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

Ellis & Baldwin (1984)

Aberration



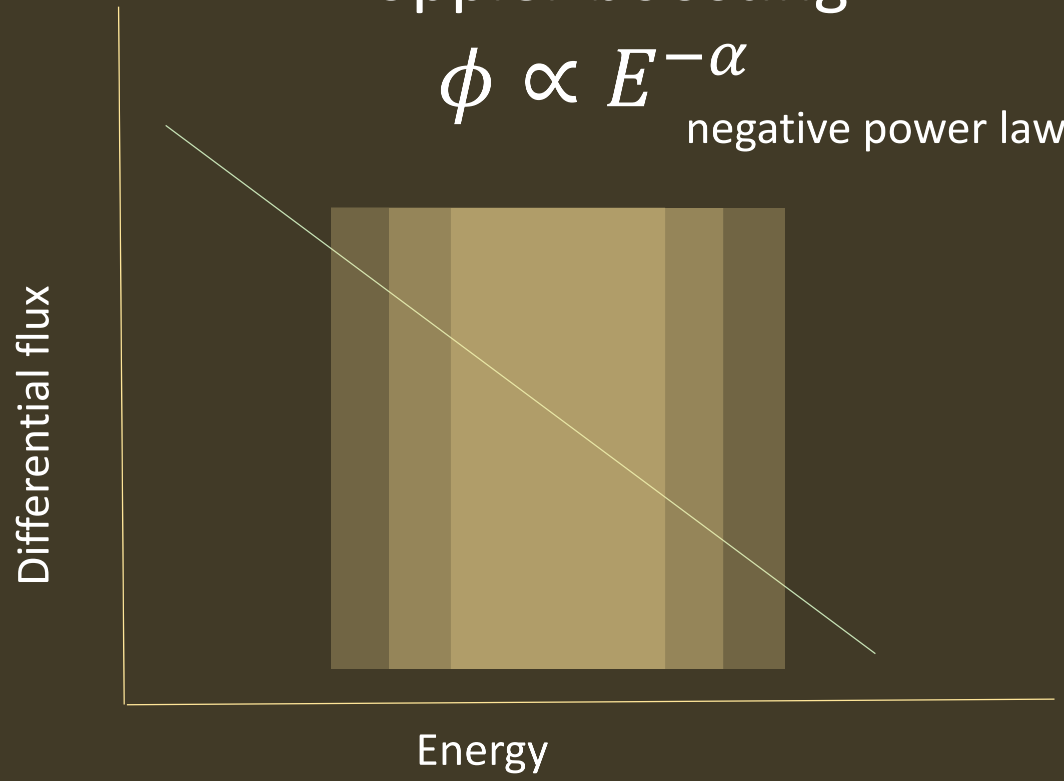
$$\tan\phi = \frac{\sin\theta}{\gamma * cos\theta - \frac{v}{c}}$$

+

Doppler boosting

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

negative power law



Flux limited catalog -> more sources in direction of motion

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

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;

amplitude D of the quasi-sinusoidal output of the interferometer provides information on the source population at flux densities where there is approximately one source per beam area, $S \approx 0.2$ Jy, about 10 times deeper than the catalogue for the 4C data. It is the large number of beam areas in the survey, about 9.5×10^4, which provides the good statistical accuracy which is necessary for our purposes. Hughes & Longair (1967) analysed these data for evidence of anisotropy in the source population. They found none, but again did not set a numerical limit on any dipole anisotropy present. Analysis of the data in their table 1 on the median values of D in areas 2^h in RA by $10°$ in Dec, for a dipole term aligned with a maximum at Dec $0°$, gives an amplitude of the dipole anisotropy of $(6.9 \pm 5.6) \times 10^{-3}$ in a direction towards RA $01^h.7$. The quoted error is again the statistical error arising from the finite number of independent values of D. In practice the uncertainty in the constancy of the calibration of sensitivity throughout the 24^h of RA is of comparable magnitude.

Needs a million sources to detect the CMB dipole velocity

Mon. Not. R. astr. Soc. (1984) 208, 377–381

On the expected anisotropy of radio source counts

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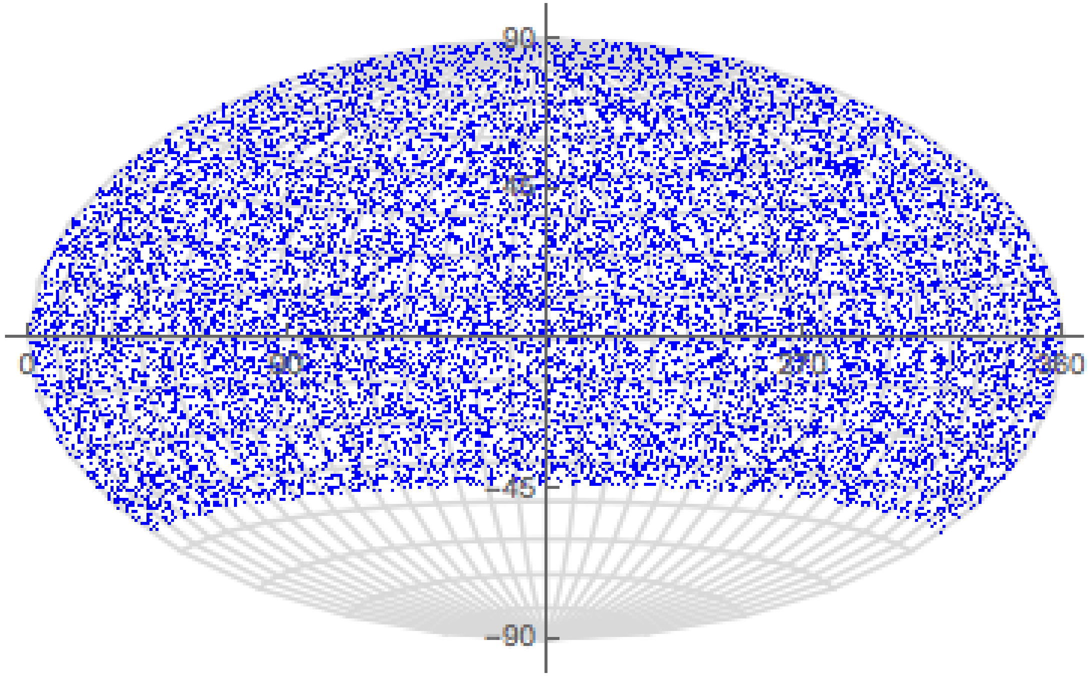
The situation anticipated by Ellis and Baldwin in 1984 now confronts us!

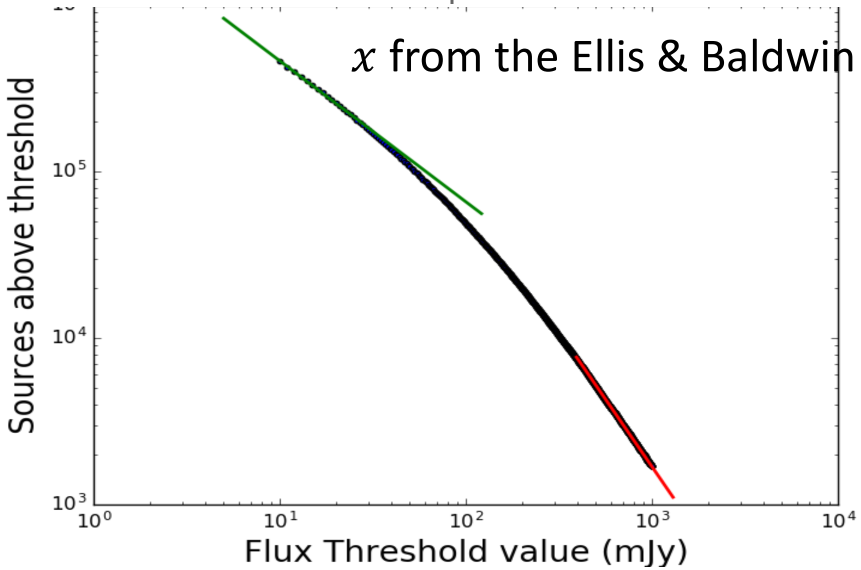
Ellis & Baldwin tests : The Cosmic Dipole Anomaly

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^o

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

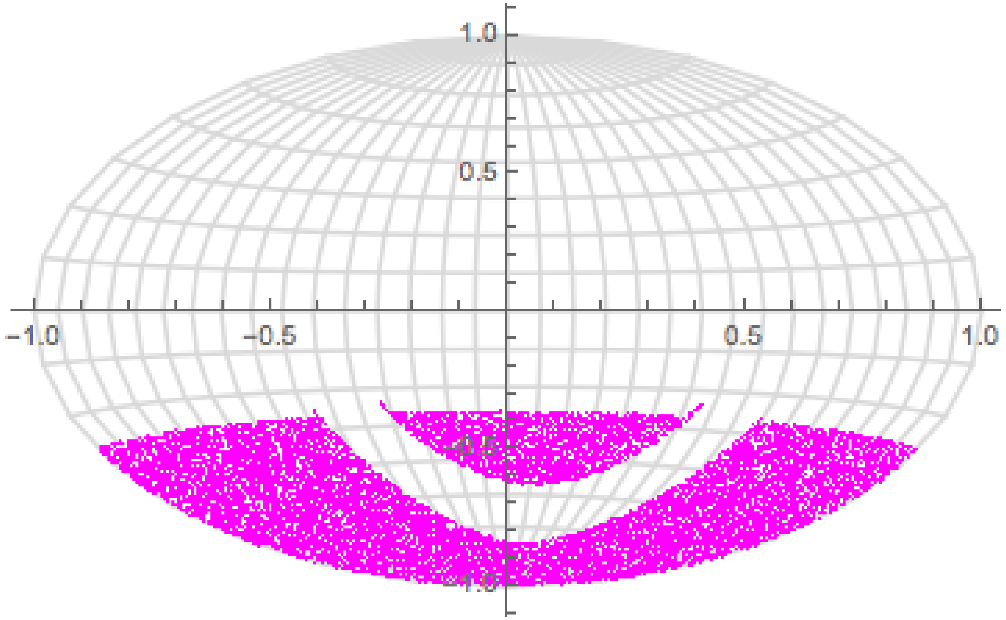


x from the Ellis & Baldwin expression

Phys. Rev. D, 78, 043519

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

Sydney University Molonglo Sky Survey (SUMSS)

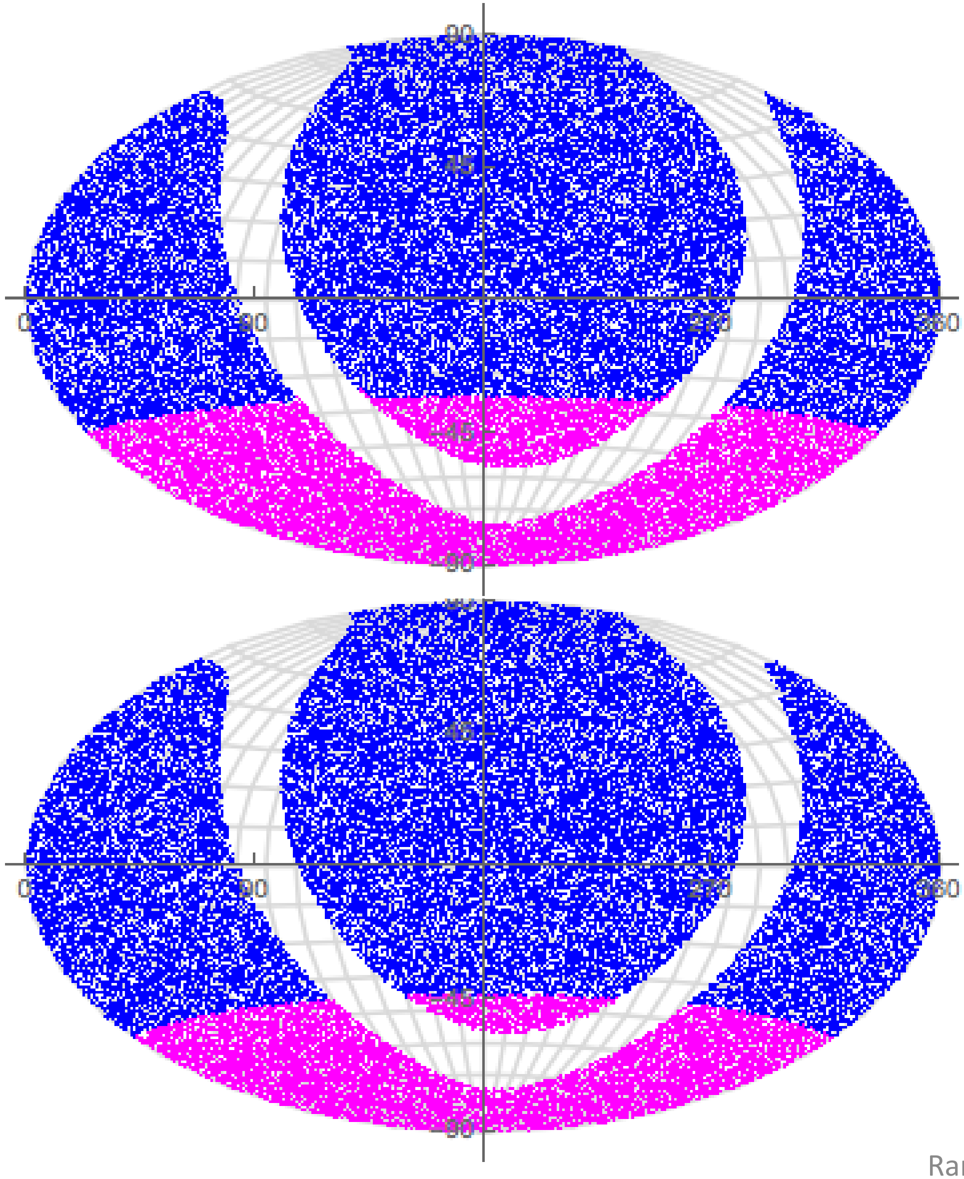


x from the Ellis & Baldwin formula

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

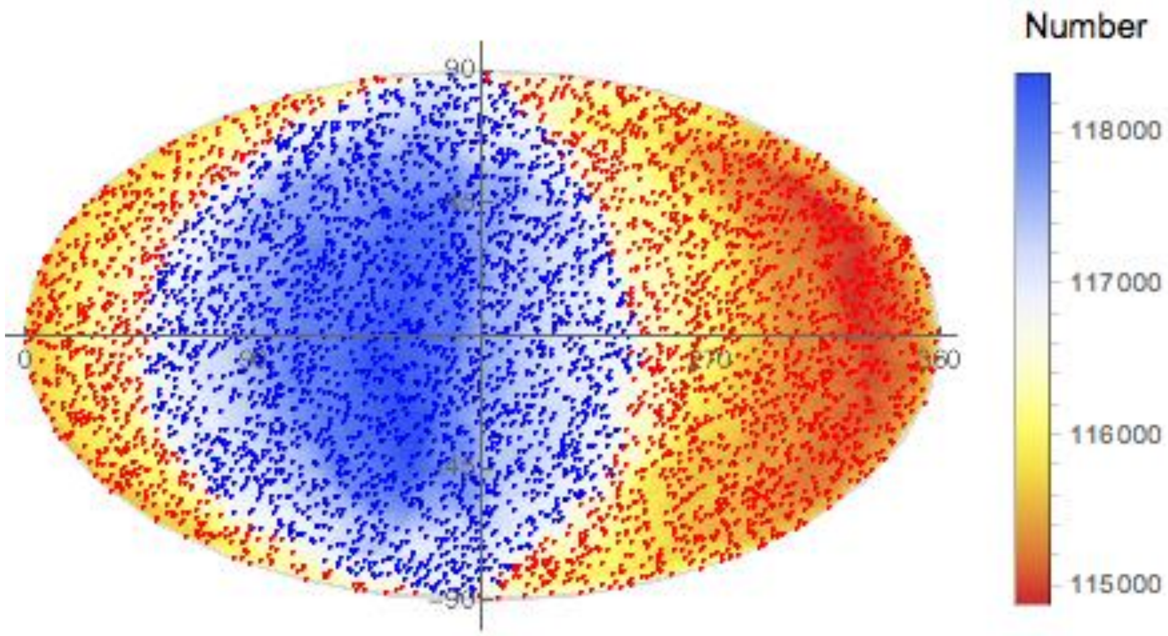
211050 radio sources. Similar sensitivity and resolution to NVSS

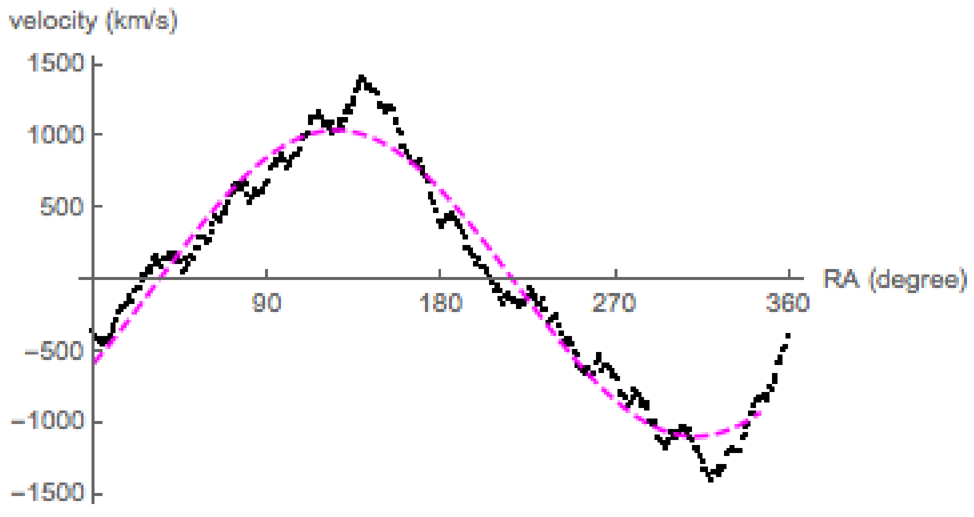
The NVSUMSS-Combined All Sky catalog



- 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 ± 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 !

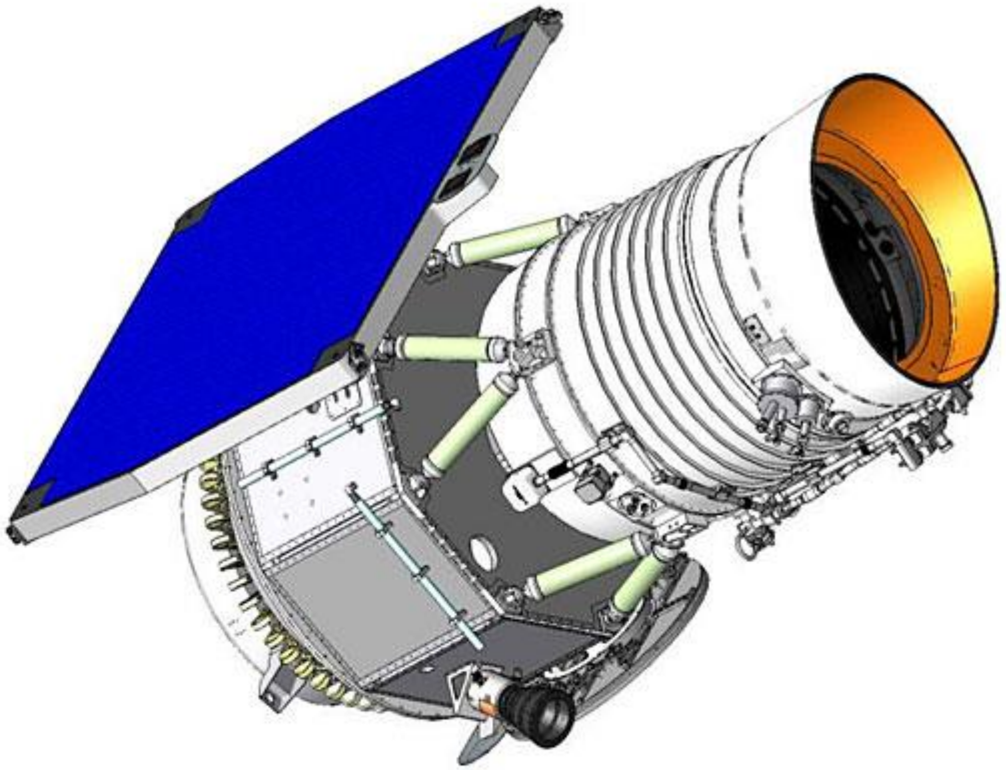
SKA phase 1 measurement ~10%

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

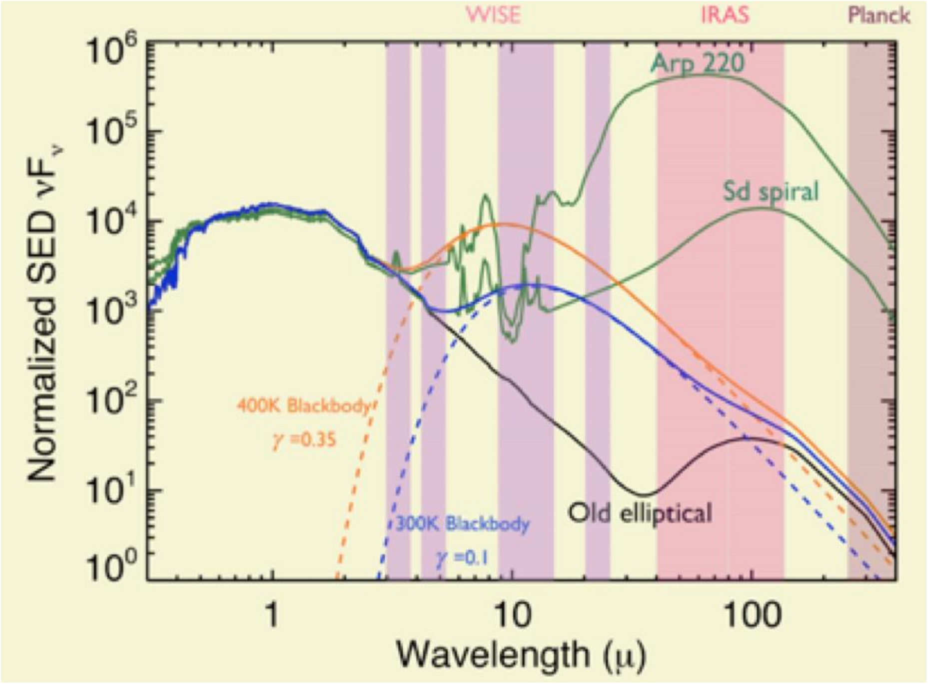
The Widefield Infrared Survey Explorer



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 • © 2021. The Author(s). Published by the American Astronomical Society.

The Astrophysical Journal Letters, Volume 908, Number 2

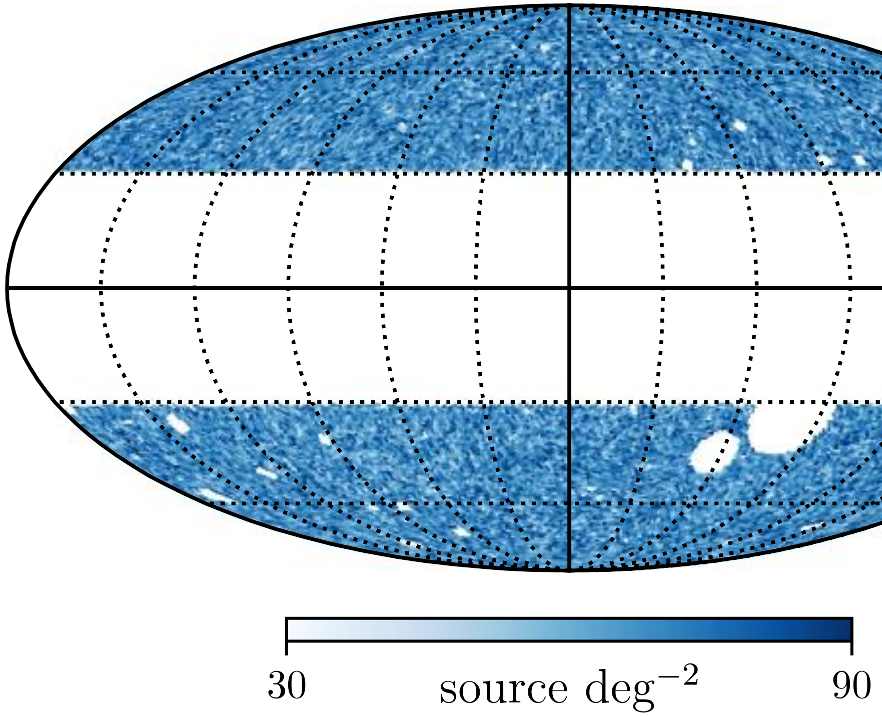
Citation Nathan J. Secrest *et al* 2021 *ApJL* **908** L51

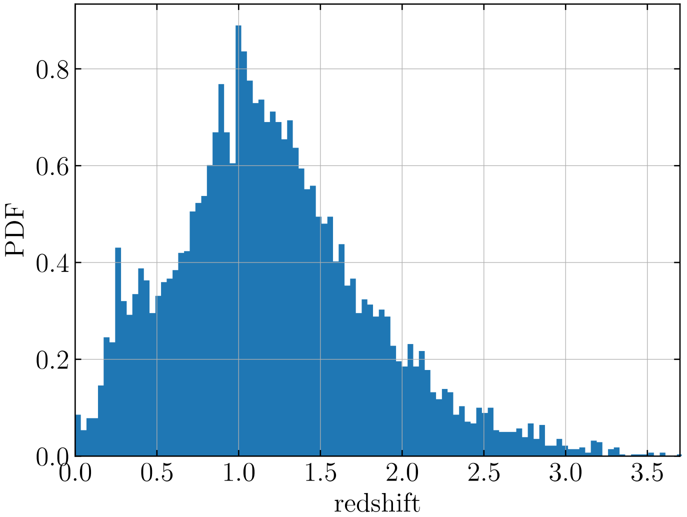
DOI 10.3847/2041-8213/abdd40

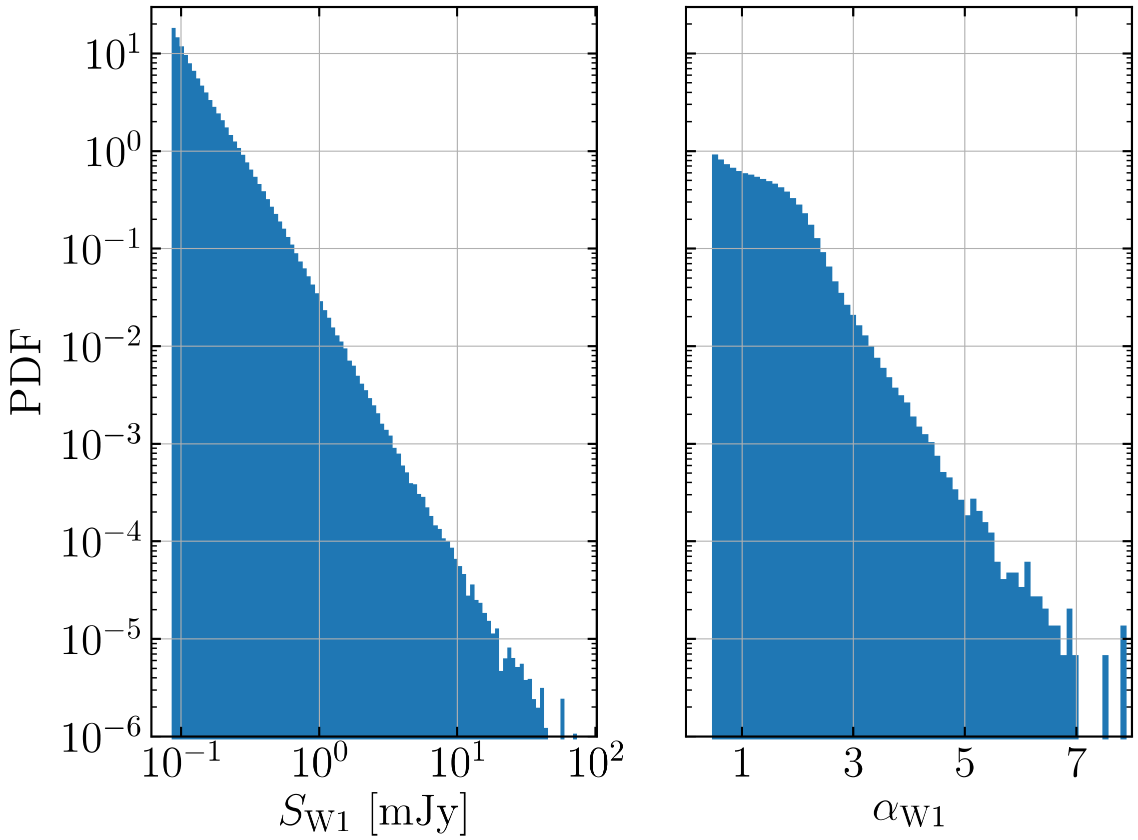
ABSTRACT

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

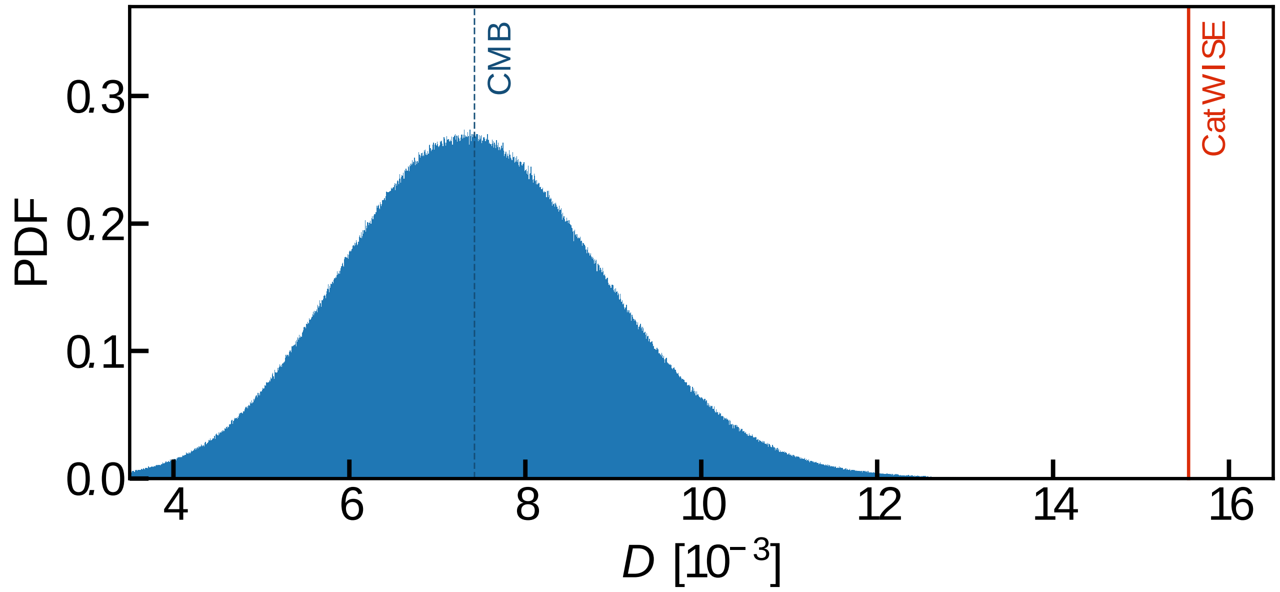


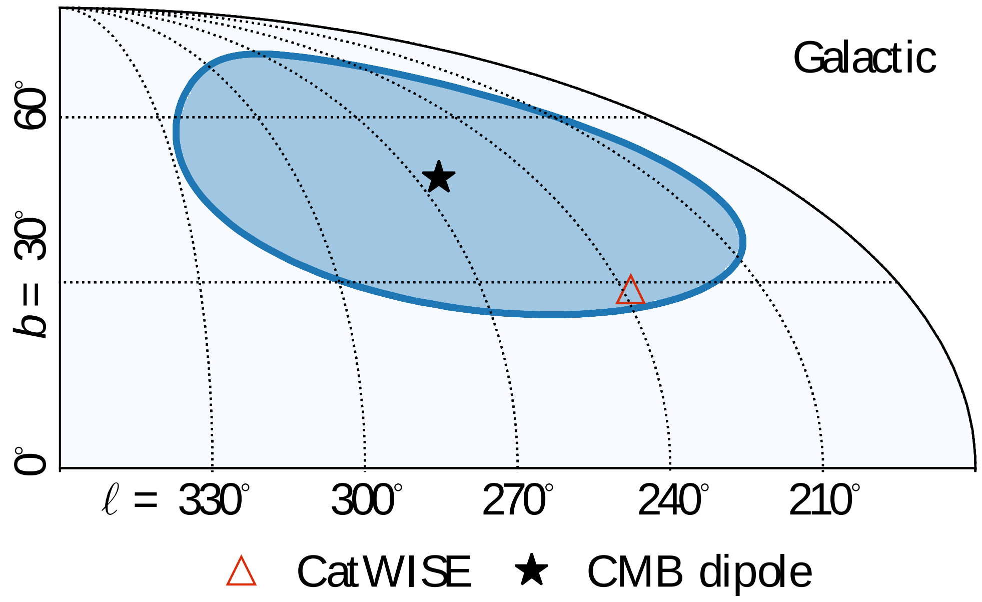




Astrophys.J.Lett. 908 (2021) 2, L51

Results



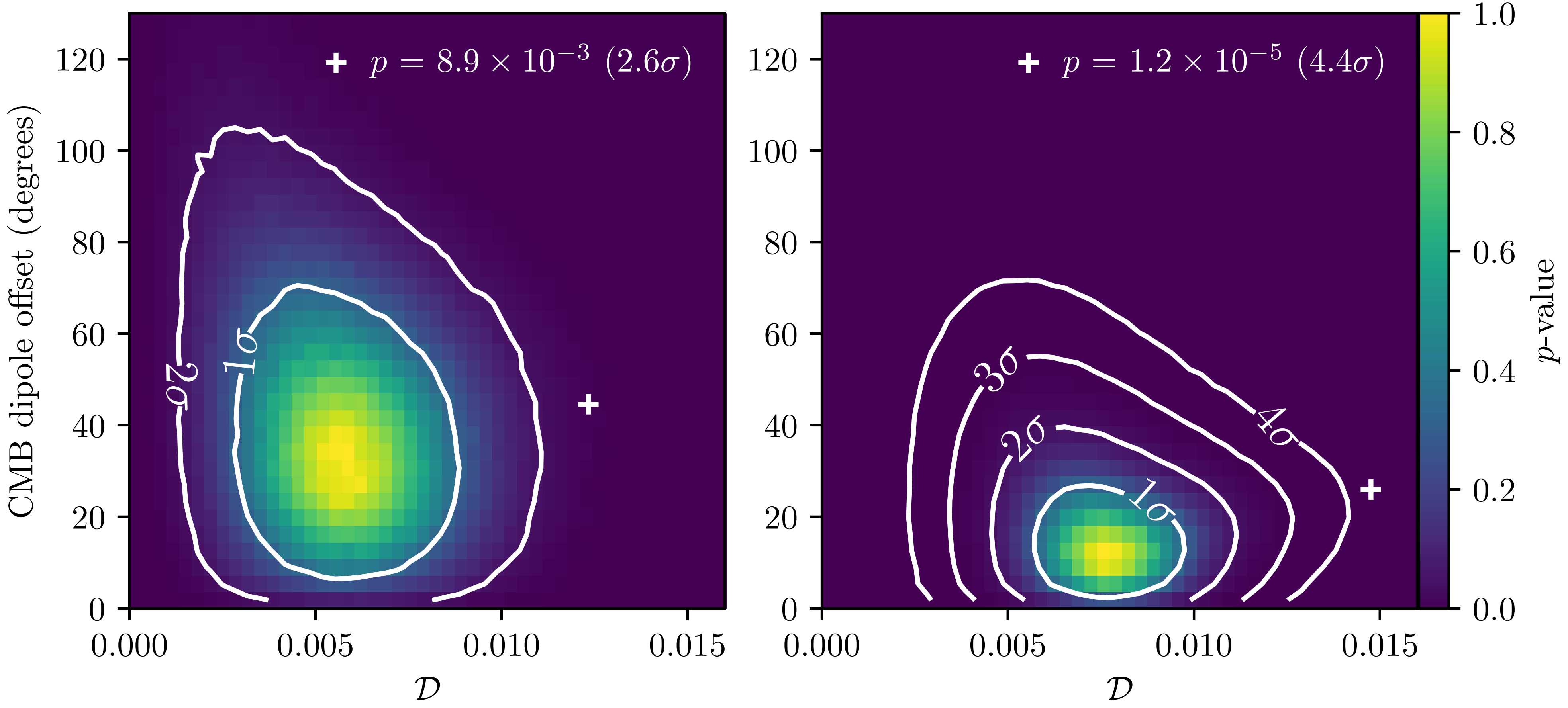


p = 5×10^{-7} (4.9 σ)

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

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

NVSS 508144 sources WISE 1.6 million sources



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)

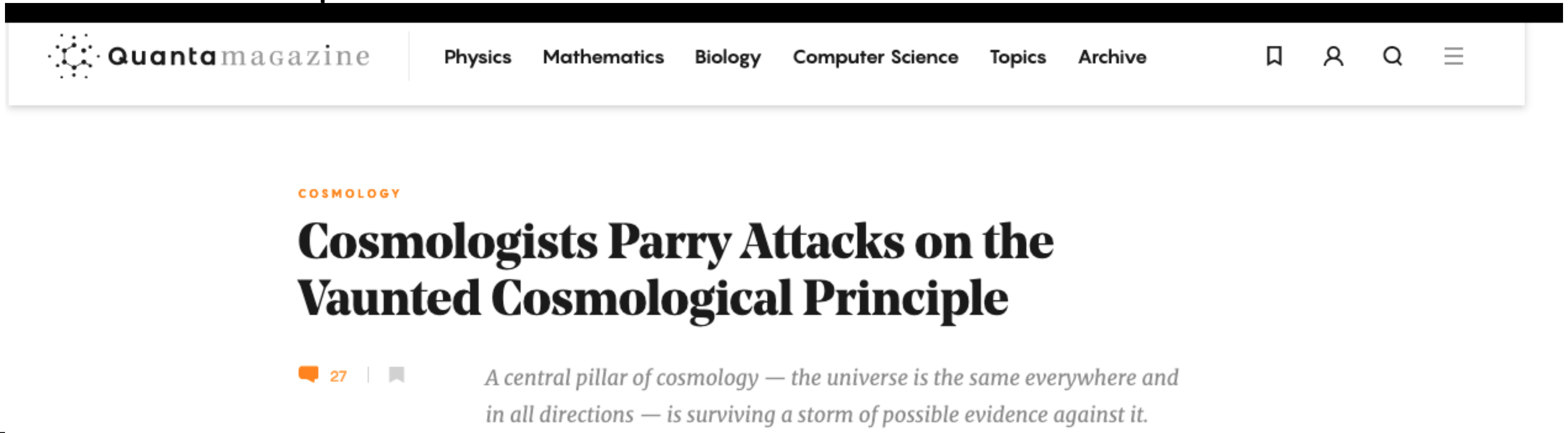
Testing the Cosmological Principle with CatWISE Quasars: A Bayesian Analysis of the Number-Count Dipole

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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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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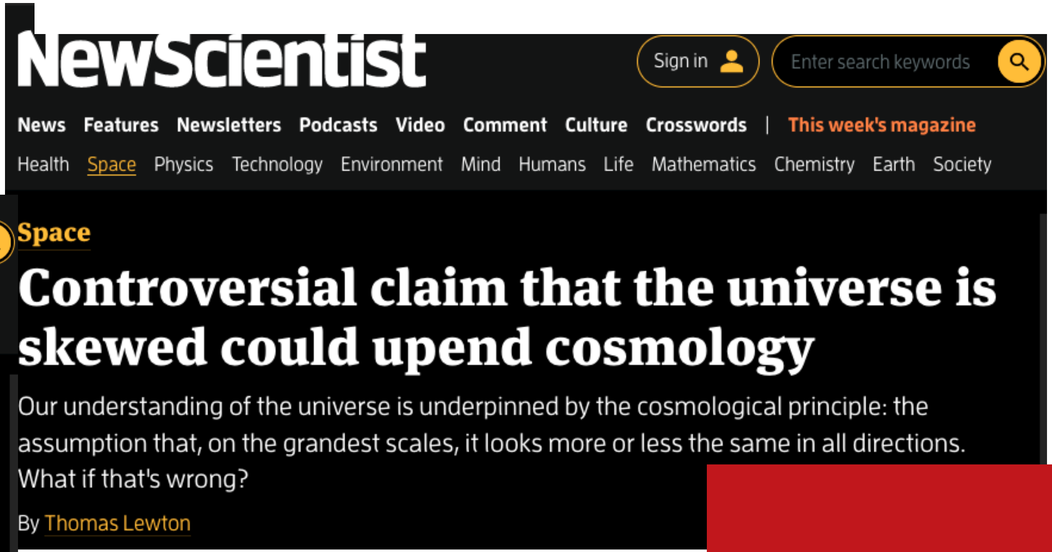
Space

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

By Leah Crane

9 March 2021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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


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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

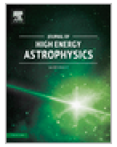
Andrei Constantin,[1,*] Thomas R. Harvey,[1,†] Sebastian von Hausegger,[2,‡] and Andre Lukas[1,§]
[1] *Rudolf Peierls Centre for Theoretical Physics, University of Oxford, Parks Road, Oxford, UK*
[2] *Astrophysics, University of Oxford, Denys Wilkinson Building, Keble Road, Oxford, UK*

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

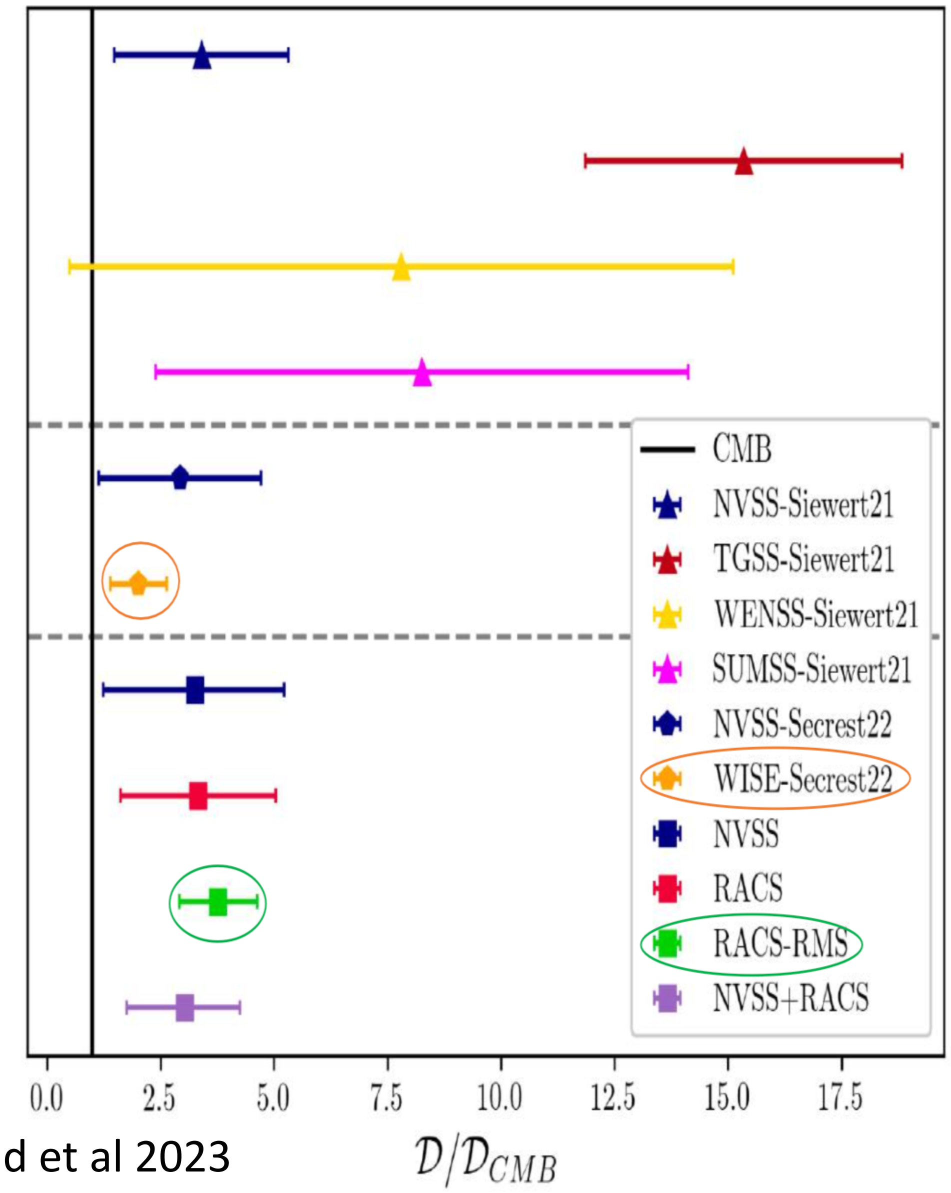
Cosmology intertwined: A review of the particle physics, astrophysics, and cosmology associated with the cosmological tensions and anomalies

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

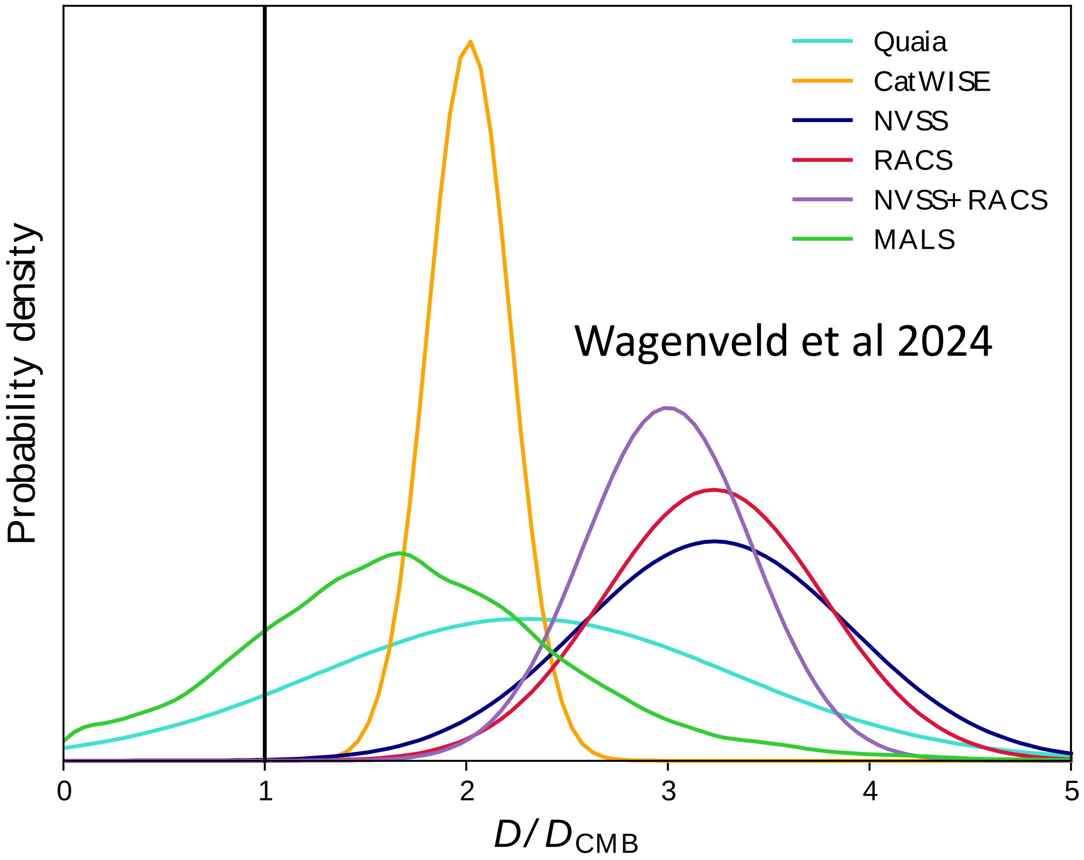
THE COSMIC RADIO DIPOLE: BAYESIAN ESTIMATORS ON NEW AND OLD RADIO SURVEYS



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

Wagenveld et al 2023

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



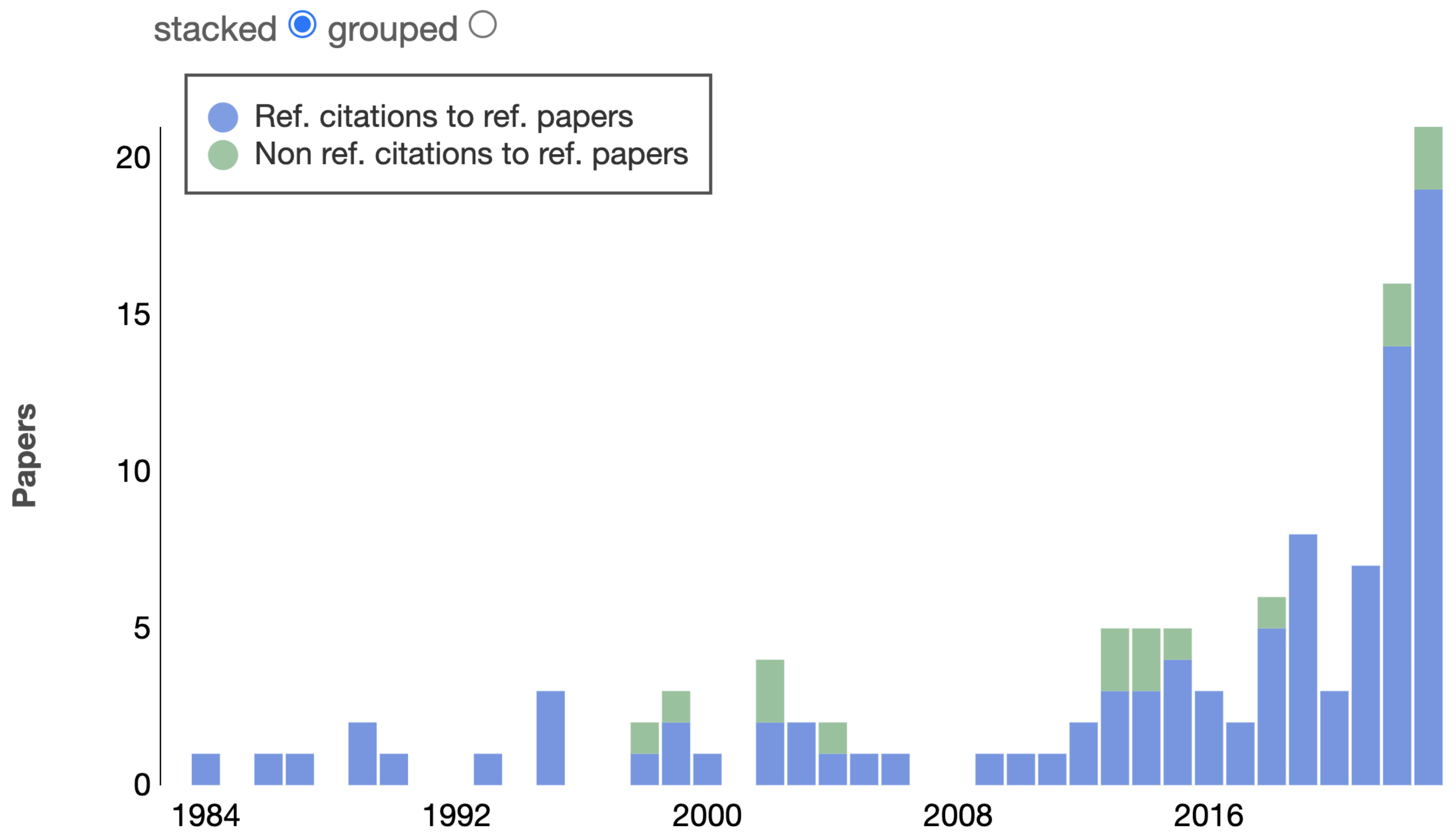
Wagenveld et al 2024

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

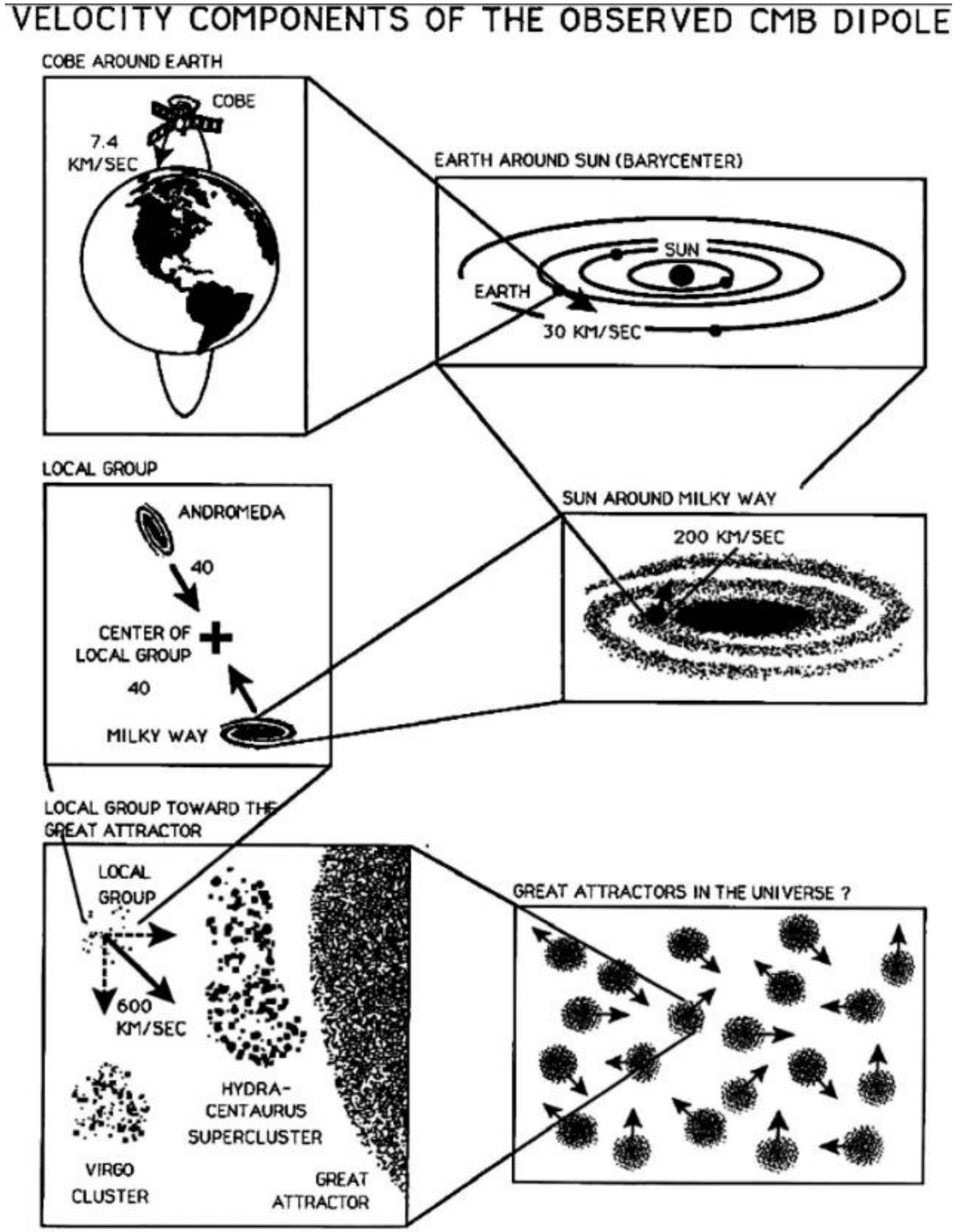
Watch out for upcoming RevModPhys review.

SKA, Euclid, SphereX

Citations to Ellis & Baldwin 1984

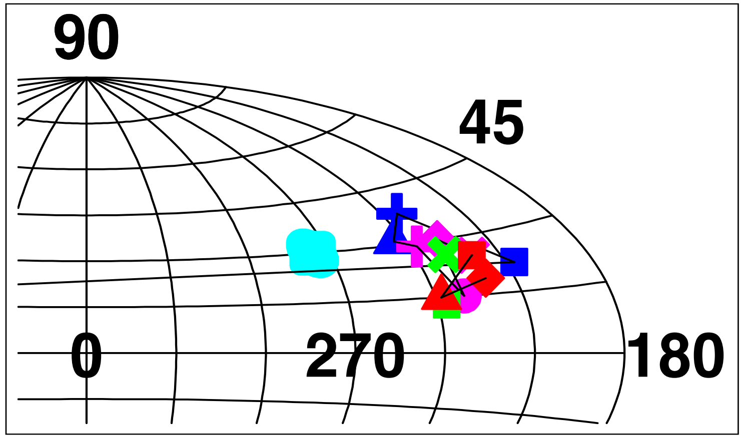


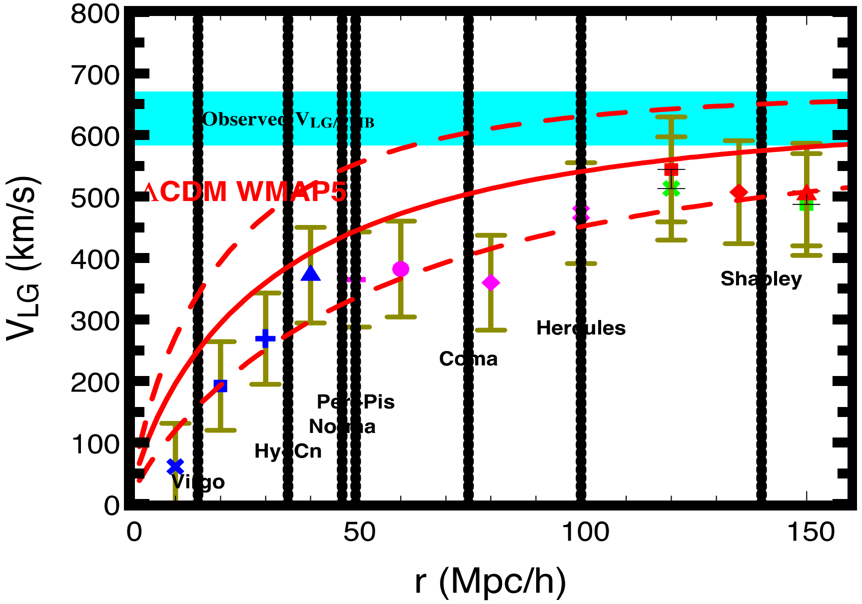
Bulk flows and a tilted Universe in SNe 1a



George Smoot, Nobel Lecture, 8 Dec 2006

Where is the cosmic 'rest frame'?

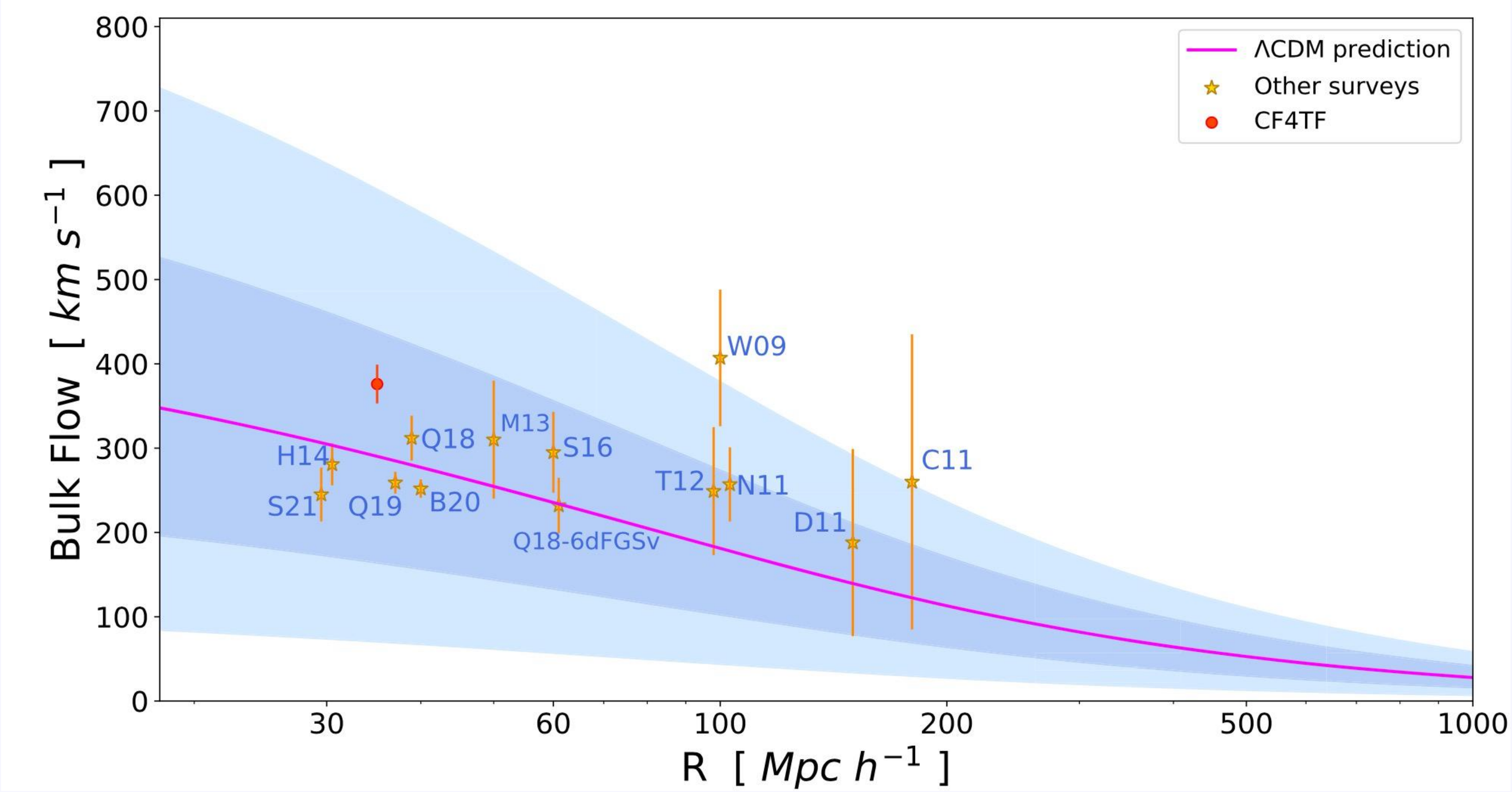




G. Lavaux, R.Brent Tully, R. Mohayaee, S. Colombi

•*Astrophys.J.* 709 (2010) 483-498

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

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

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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(±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

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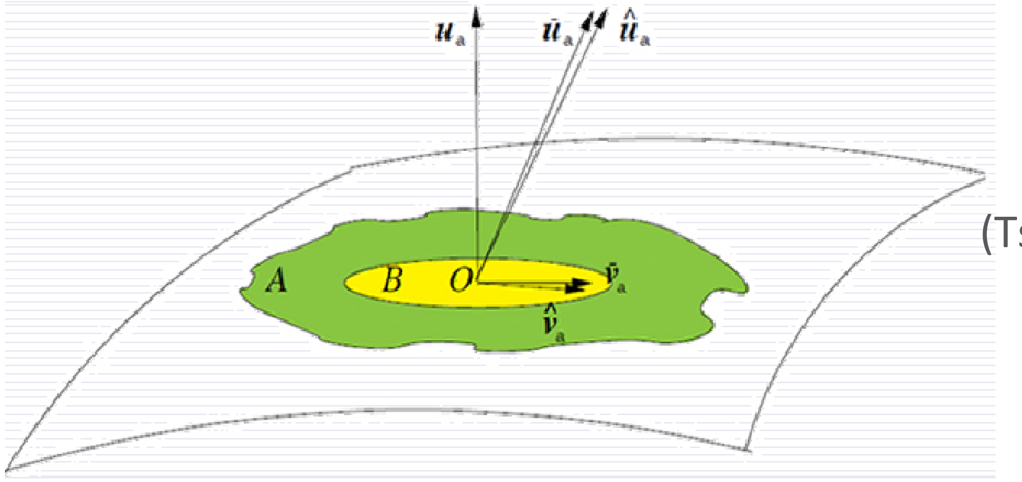
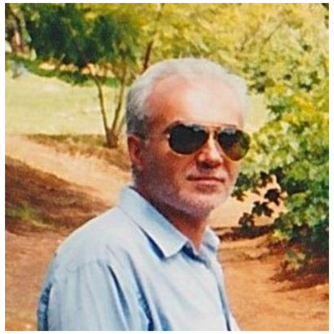
7 February 2023

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

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

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

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.**

A&A 631, L13 (2019)
https://doi.org/10.1051/0004-6361/201936373

Astronomy & Astrophysics

Letter to the Editor

Evidence for anisotropy of cosmic acceleration★

Jacques Colin[1], Roya Mohayaee[1], Mohamed Rameez[2], and Subir Sarkar[3]

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

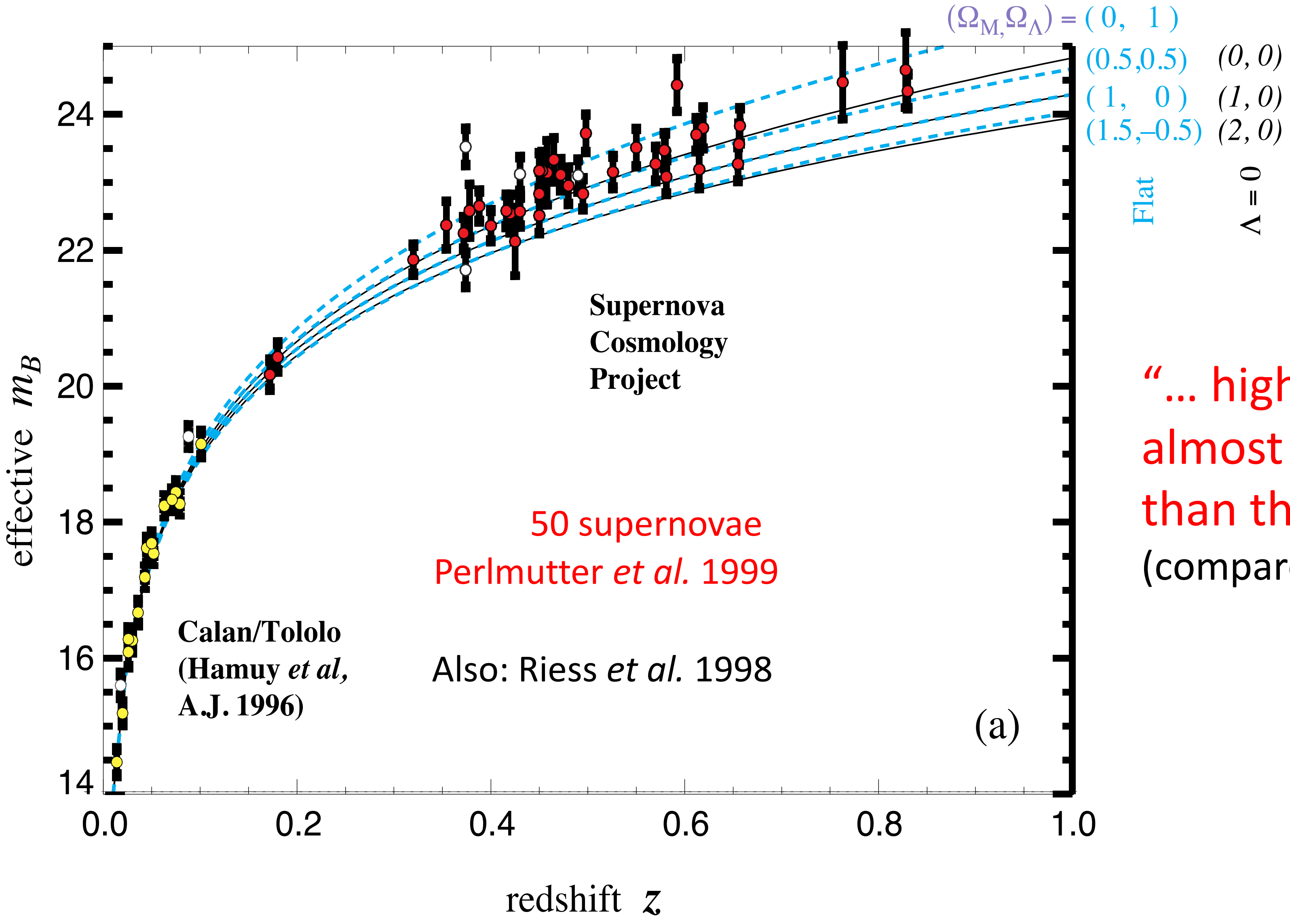
Ensuing debate

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 $S = 0.0262$ ($\Rightarrow d \sim 100$ 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)

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

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

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

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

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

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

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

Kinematic

Visser 2004

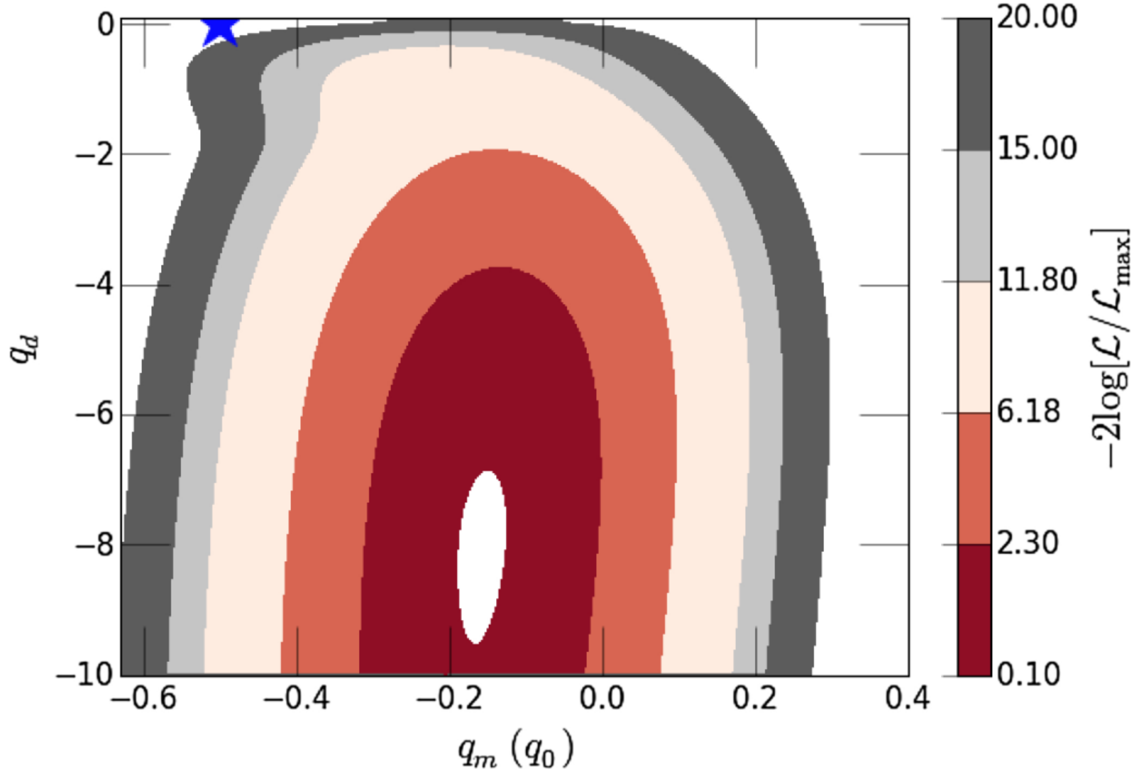
$q = \frac{\Omega_M}{2} - \Omega_\Lambda$ (in ΛCDM)

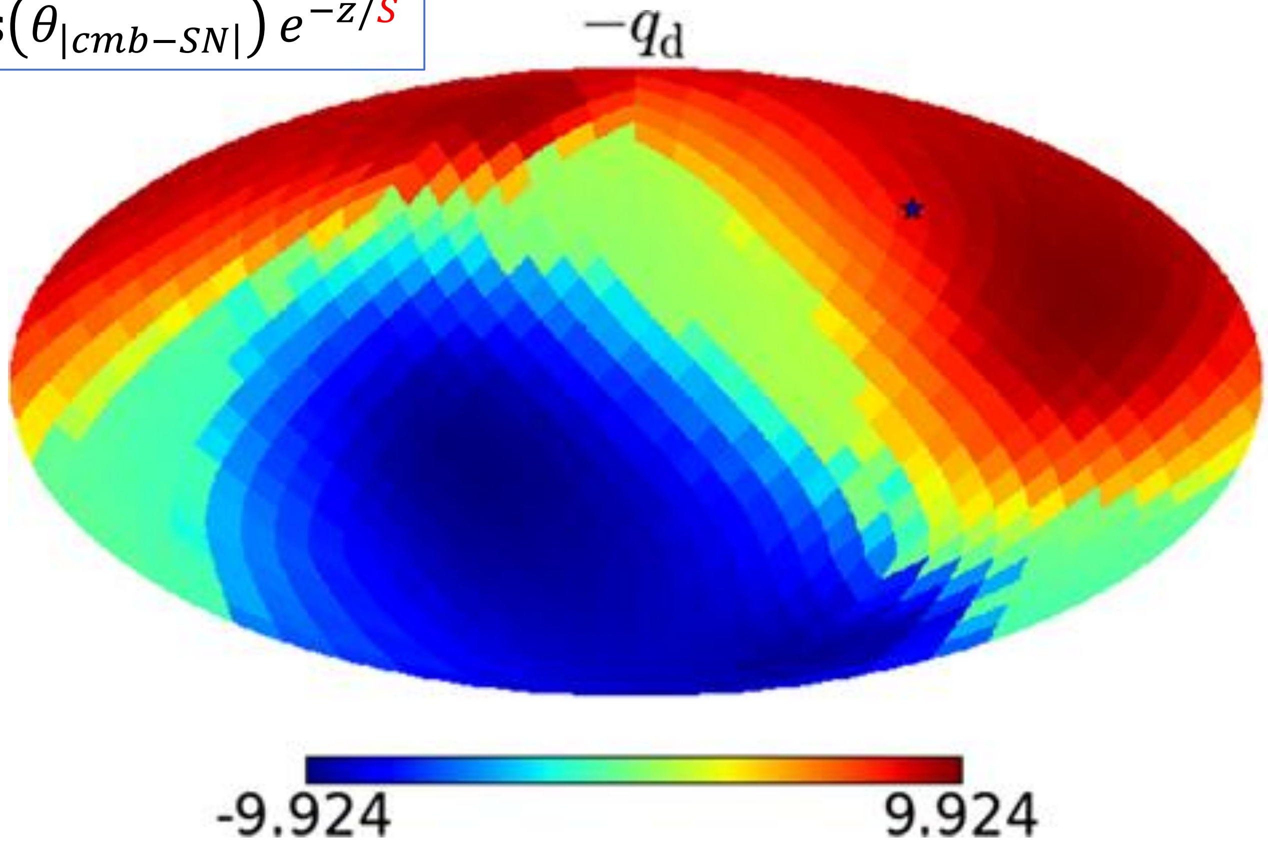
Concordance cosmology is given by

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

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* ~ 0.1. Statistically significant @ 3.9 σ

$q_d >> q_m$

The statistical significance of the Universe accelerating isotropically is <1.4σ!

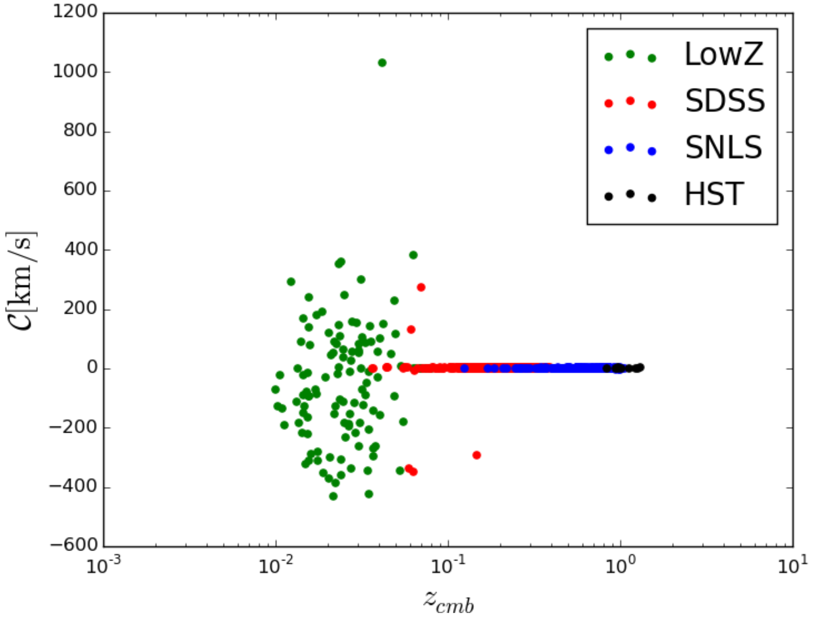
Cosmic acceleration, (and dark energy) may simply be an artefact of our being located inside a 'bulk flow'
… in accordance with the prediction of Tsagas (2011)

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

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

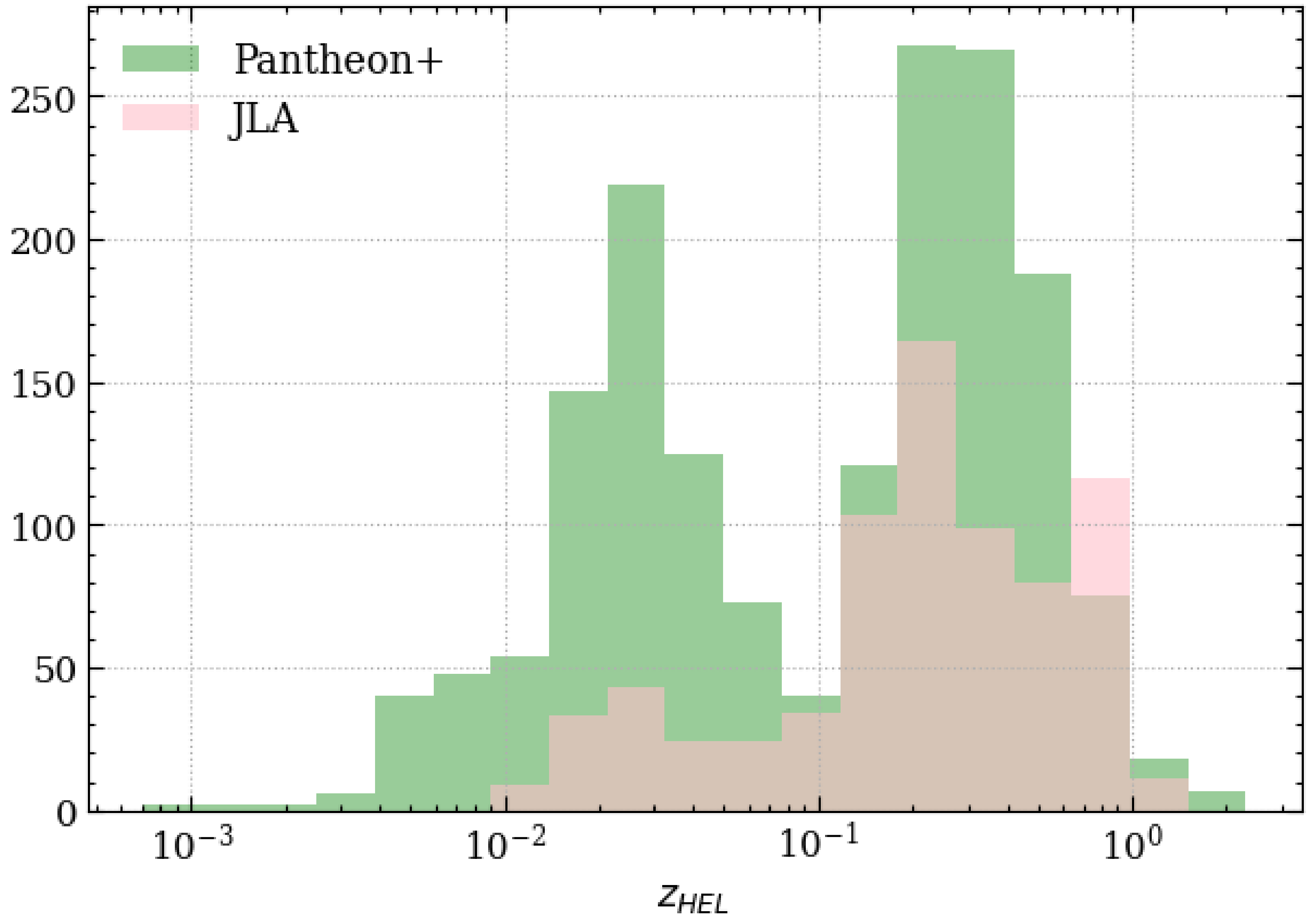


$$1 + z_{hel} = \left(1 + z_{pec}^{hel}\right) \times (1 + \bar{z}) \times \left(1 + z_{pec}^{SN}\right)$$

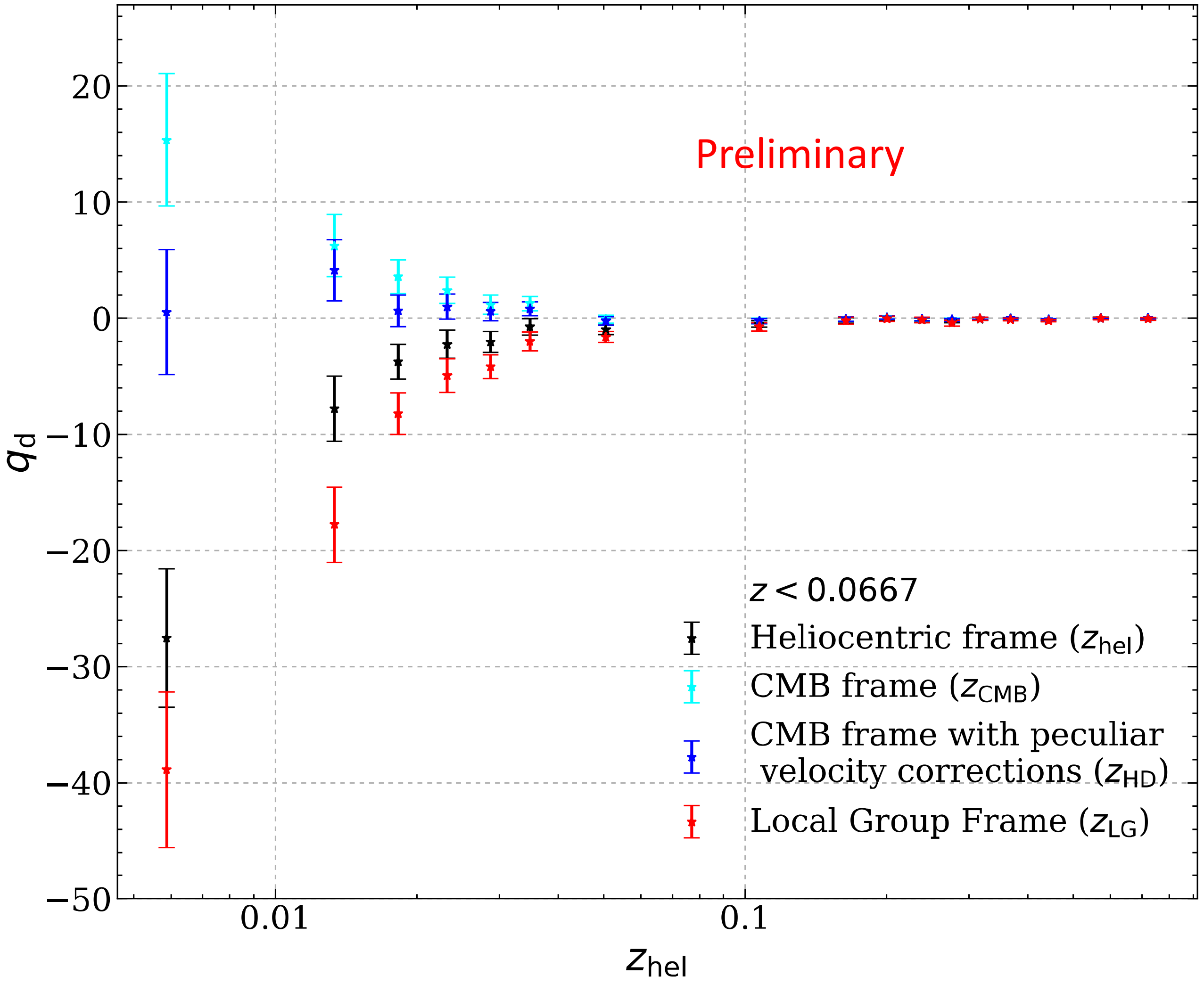
$z_{hel} \rightarrow measured$

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

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

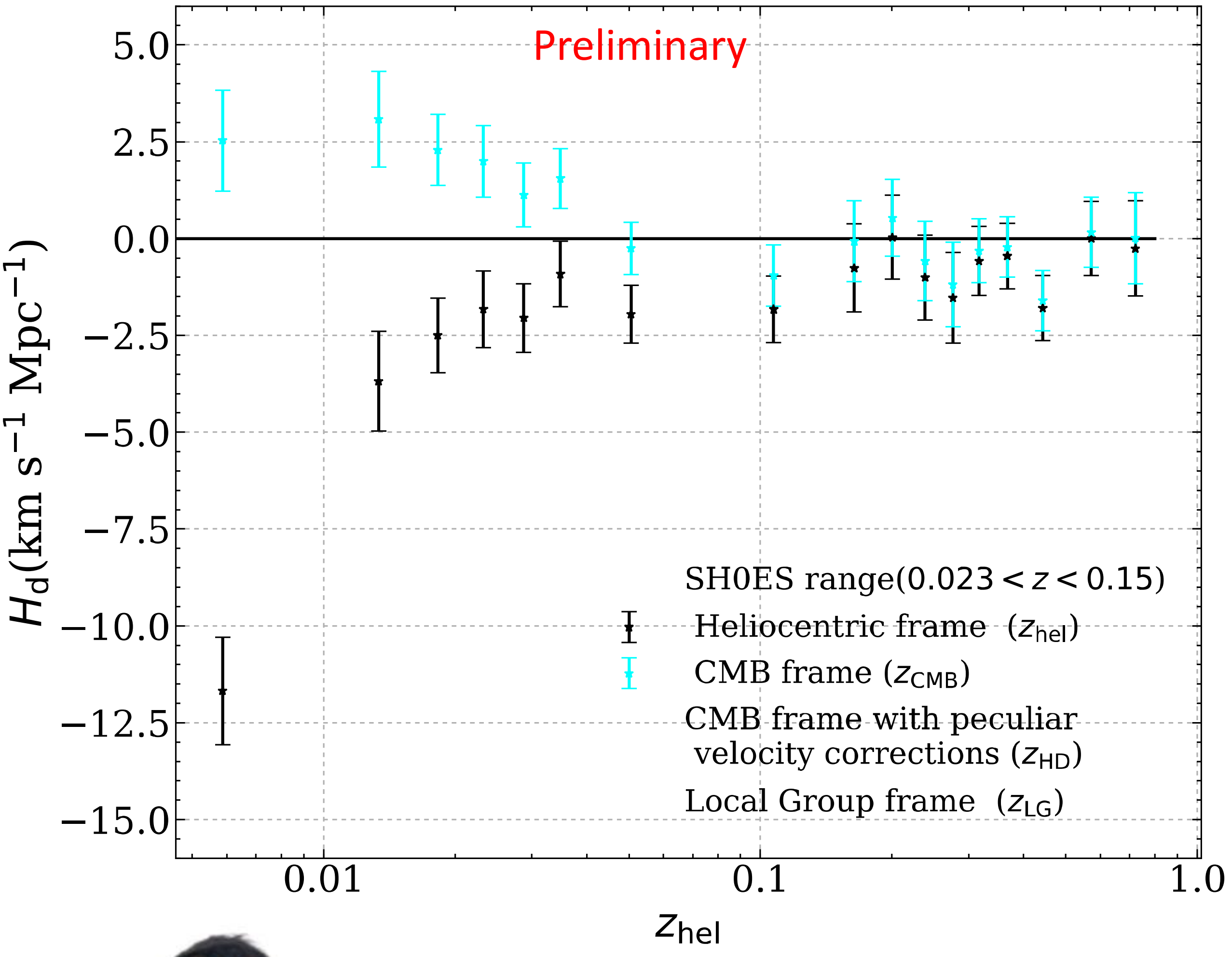


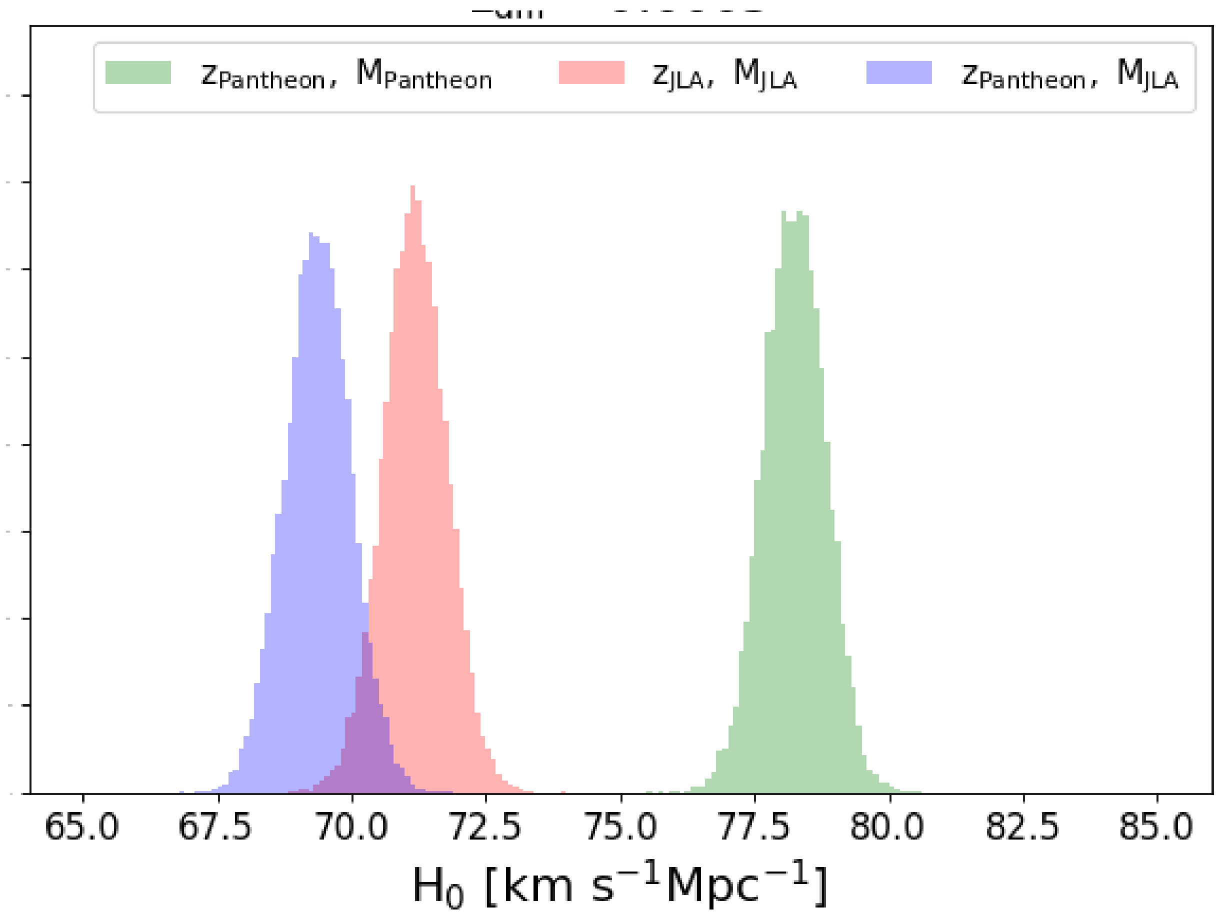
Various changes in terminology



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

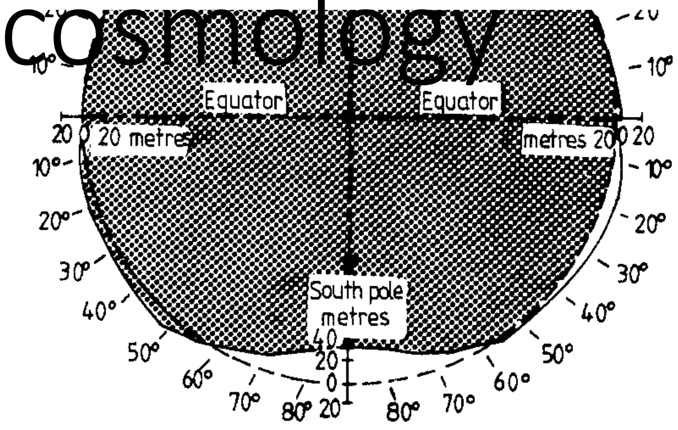
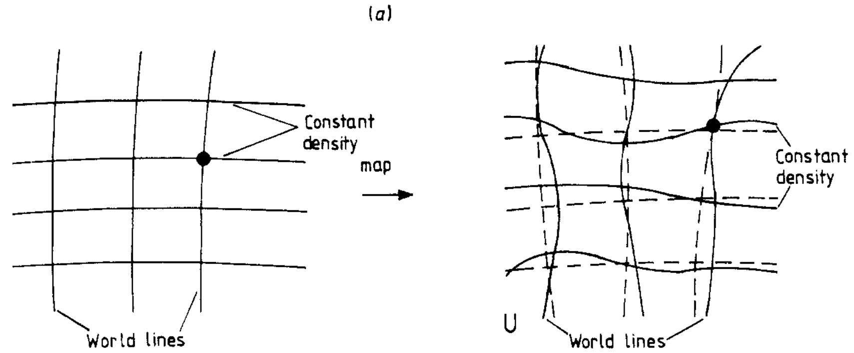


Figure 1. (*a*) An exactly uniform and spherically symmetrical FLRW universe U′ mapped into the lumpy universe U so as to give the best fit possible. (*b*) An exactly spherical sphere fitted to the lumpy world to give the best fit possible.

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.

The ‘fitting problem’ in cosmology 1699



ion

mology aims at finding the large-scale matter distribution and spacetime the universe from astronomical observations. There are broadly speaking approaches that have been applied to this problem.

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

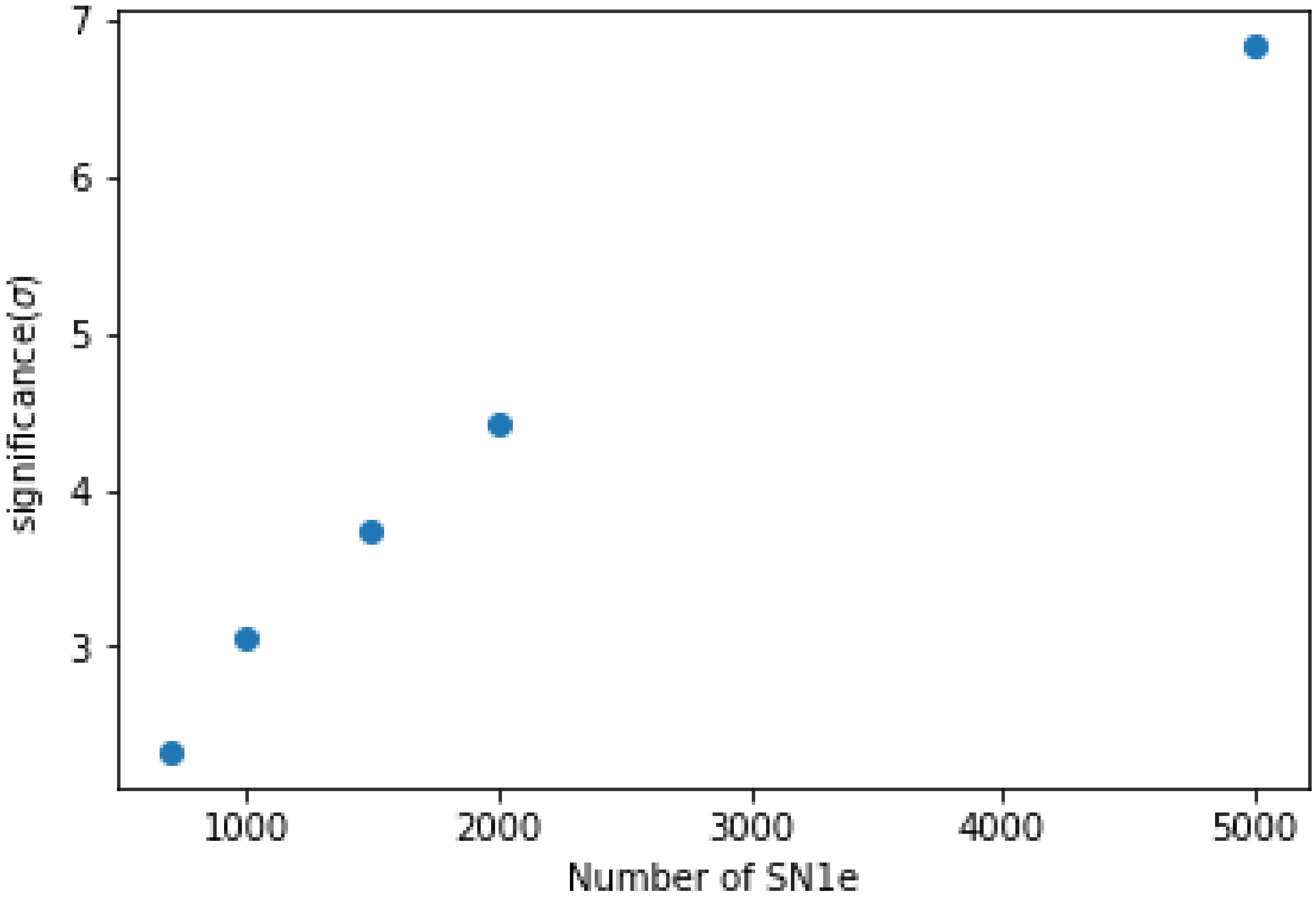
Similarly the Universe is FLRW to a precision of 10 km s^{-1} Mpc^{-1} but not to a precision of 1 km s^{-1} Mpc^{-1}

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

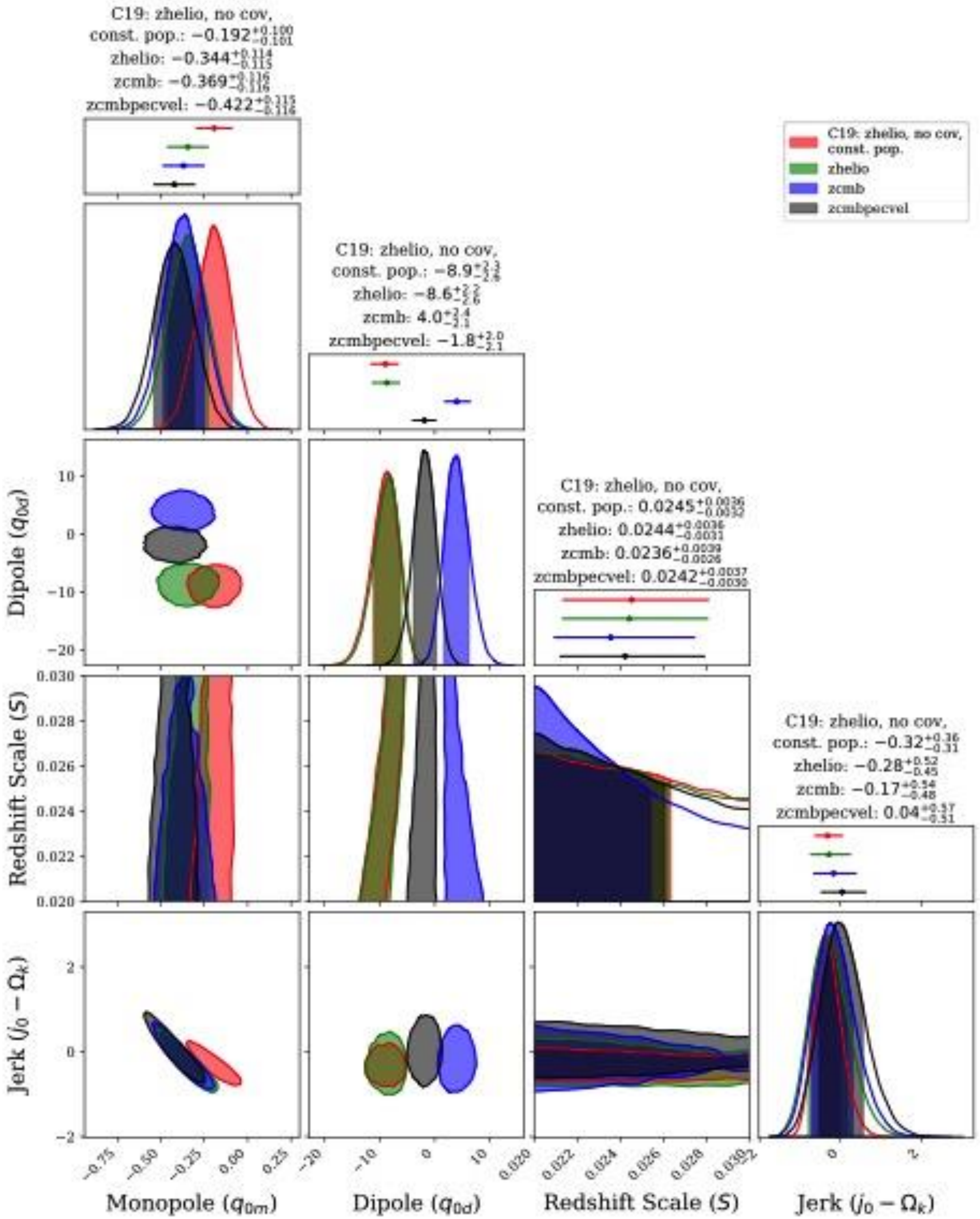
Subir Sarkar is Emeritus Professor at the Rudolf Peierls Centre for Theoretical Physics, University of Oxford.

The peculiar velocities question

- Rubin & Heitlauf (2019) demonstrate that

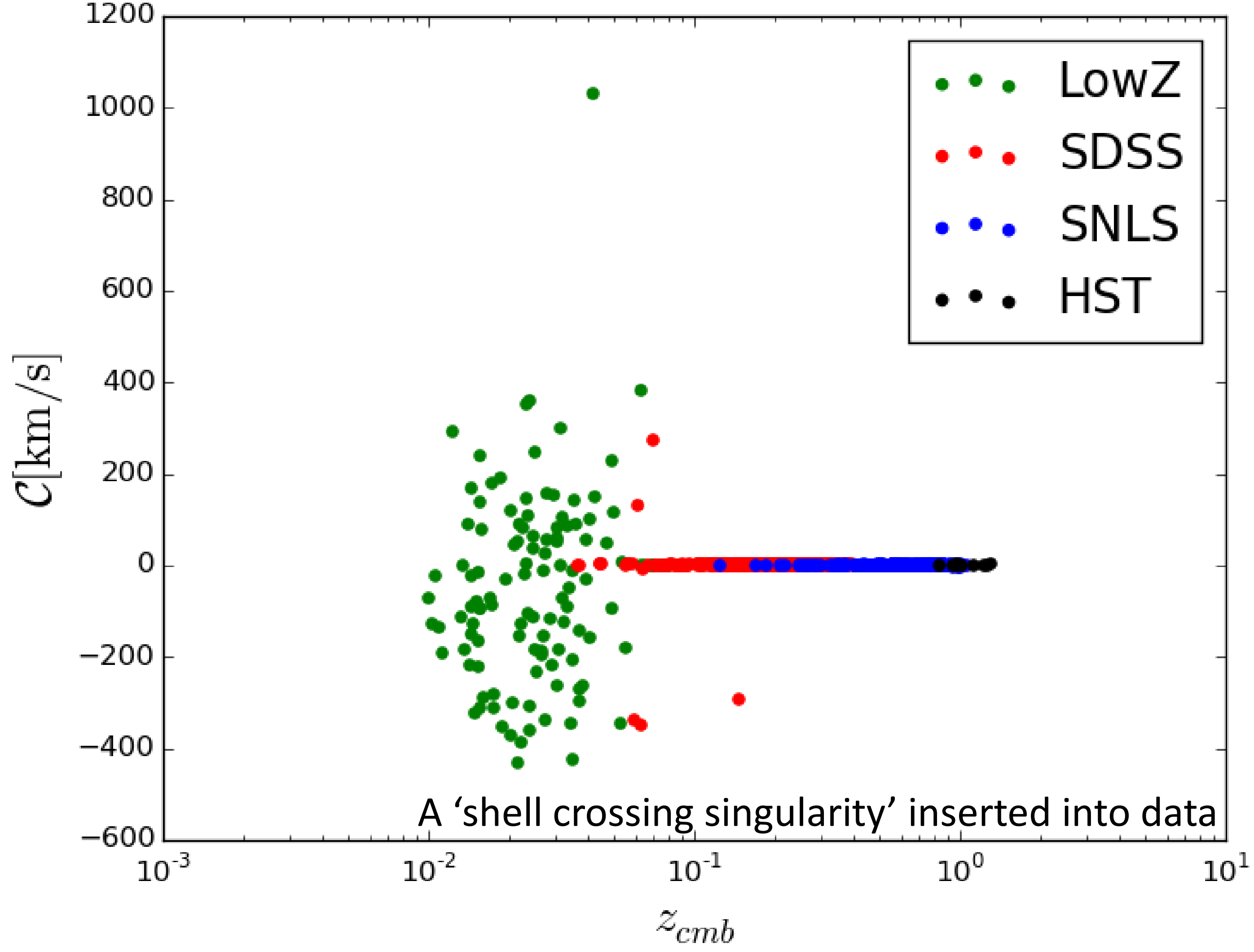
  - If the correction for the motion of the observer w.r.t. the CMB rest frame is introduced, the direction of the dipole in *q reverses*

  - Only when further correction for peculiar velocities is introduced, does the dipole in *q* effectively disappear



’Untilting’ the Universe

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

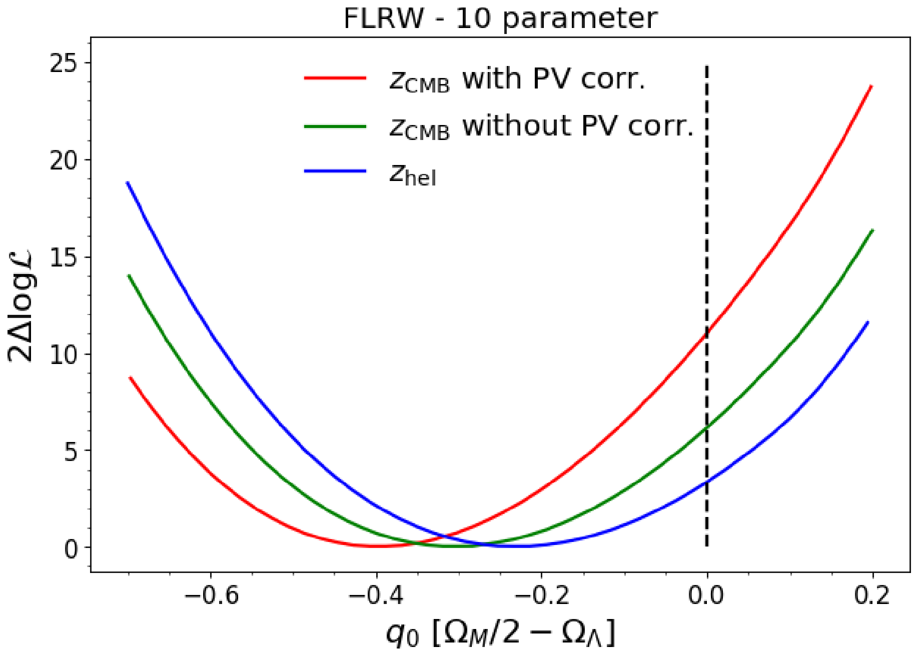


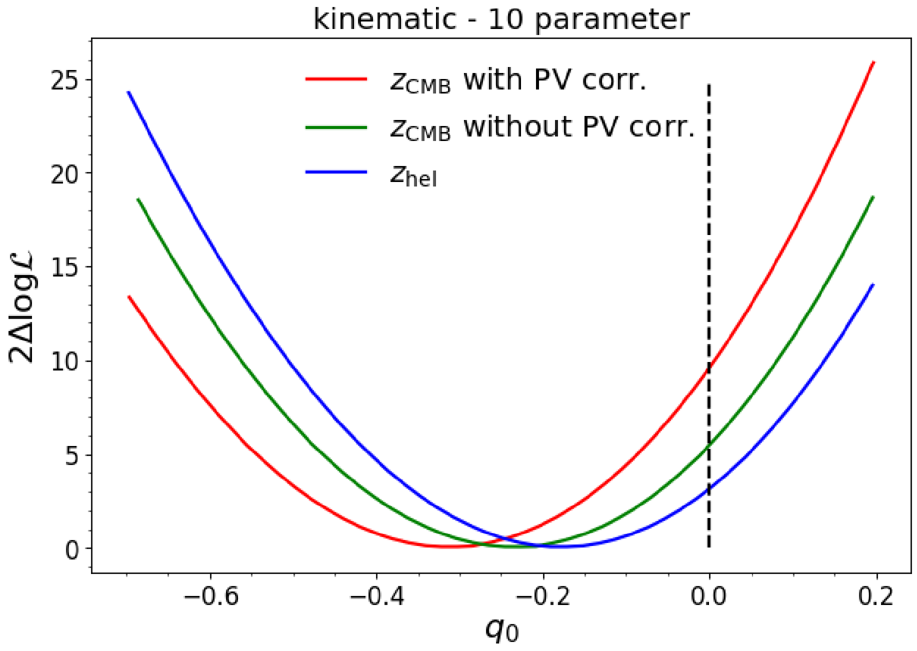
SNe Ia at $z > 0.06$ are assumed (arbitrarily) to be in the CMB rest frame (only uncorrelated 150 km/s in error budget)

Flow model (Streaming Motions of Abell Clusters, Hudson 2004) has a ~687 ± 203 km/s residual bulk flow

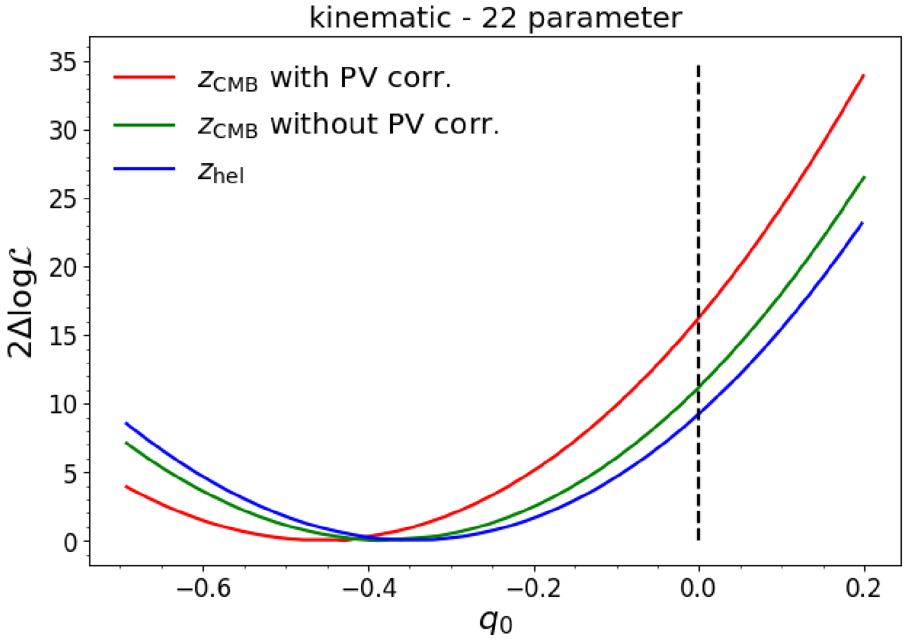
About ~half the evidence (relative dimming of high-z SNe has to be put into the data), in the process introducing an arbitrary discontinuity!

$$\Delta\mu_{\rm pv} = \frac{5}{\log(10)}\frac{v}{zc} = \frac{5}{\log(10)}\frac{687}{0.067\times c} = 0.074$$





About ~half the evidence (relative dimming of high-z SNe has to be put into the data), in the process introducing an arbitrary discontinuity!



"“… high redshift supernovae appear almost 0.15 mag (~15% in flux) fainter than the low redshift supernovae” (compared to expectation in a $\Lambda = 0$ universe)

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

Mohayaee et al 2021 *Eur.Phys.J.ST* 230 (2021) 9

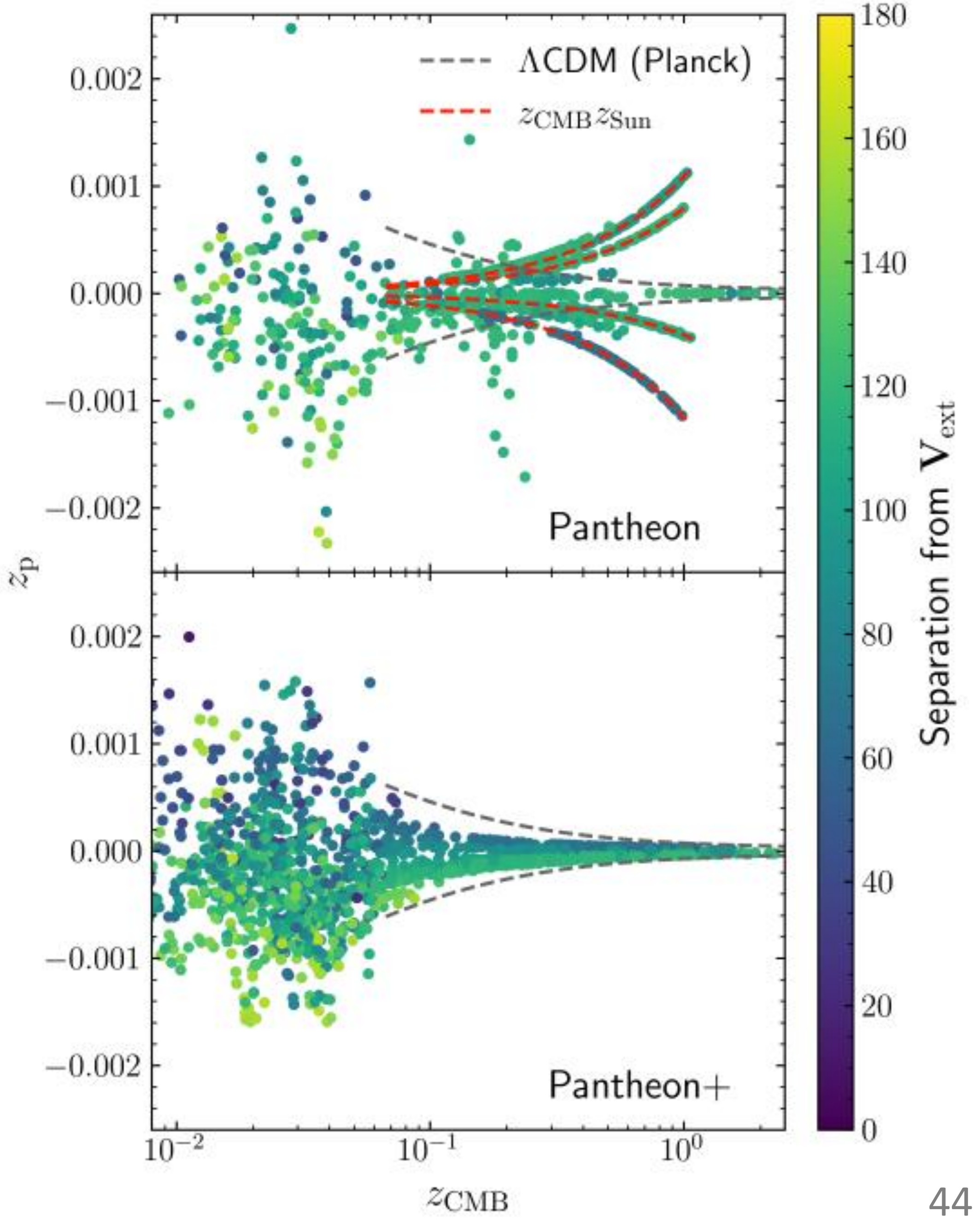
Things get weirder in later SNe Ia datasets

E.g. Carr et al 2022 on Pantheon+ peculiar velocities

6.3. *Velocities beyond $r_{\rm max}$*

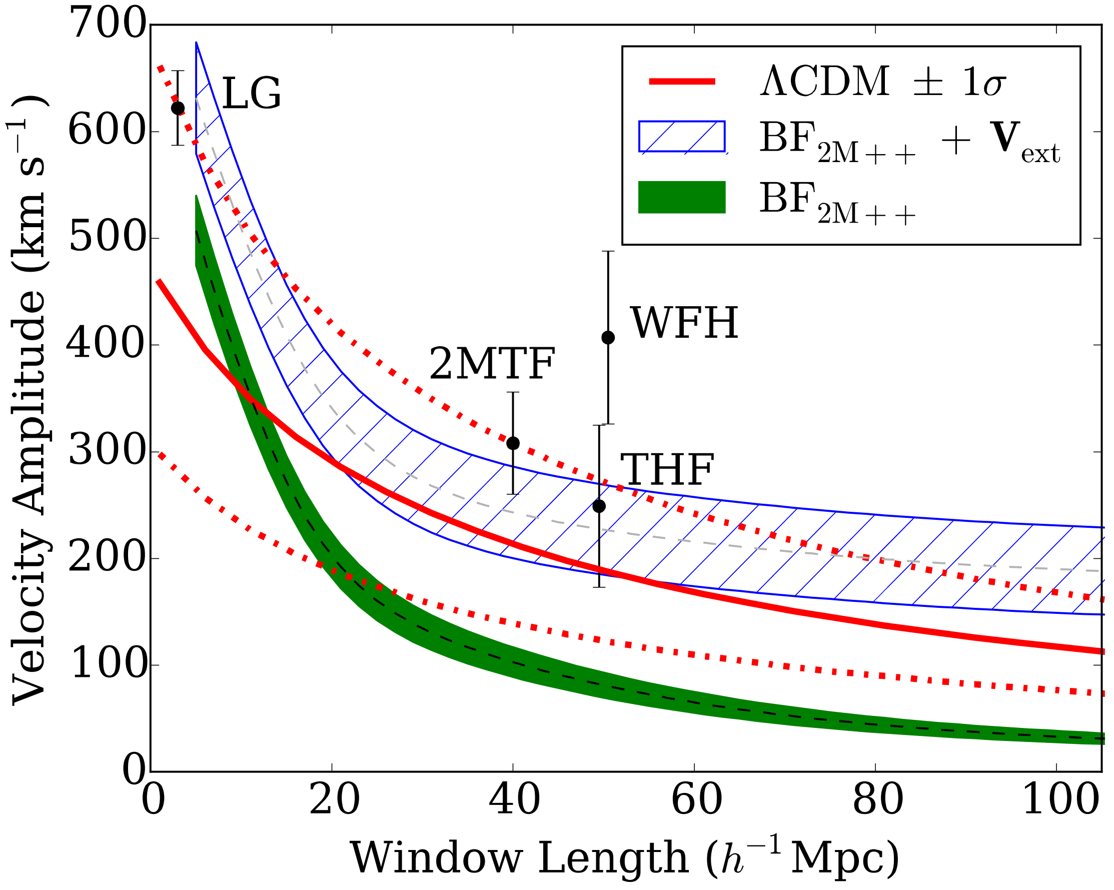
It is difficult to properly account for velocities outside $r_{\rm max}$ because we do not have an adequate measurement of the density field to predict individual velocities precisely. However, we expect velocities to continue to behave largely according to the bulk flow trend beyond $r_{\rm max}$ as a consequence of ΛCDM large scale structure. In standard ΛCDM a theoretical bulk flow magnitude of $\sim 20\ {\rm km\,s^{-1}}$ is expected even for a sphere with radius $z \sim 1$ (gray dashed lines in Figure 9). Accordingly, peculiar velocities of galaxies outside $r_{\rm max}$ should not be set to zero.

To ensure a smooth transition across $r_{\rm max}$ we have chosen to model the bulk flow as a decaying function consistent with ΛCDM expectations, and in the direction of the bulk flow of the 200 h^{-1}Mpc sphere. While there is a ΛCDM model dependence, the impact of this high-z correction on cosmological inferences is small both because the corrections are small (at most $\sim 5 \times 10^{-4}$ when in the direction of the bulk flow), and



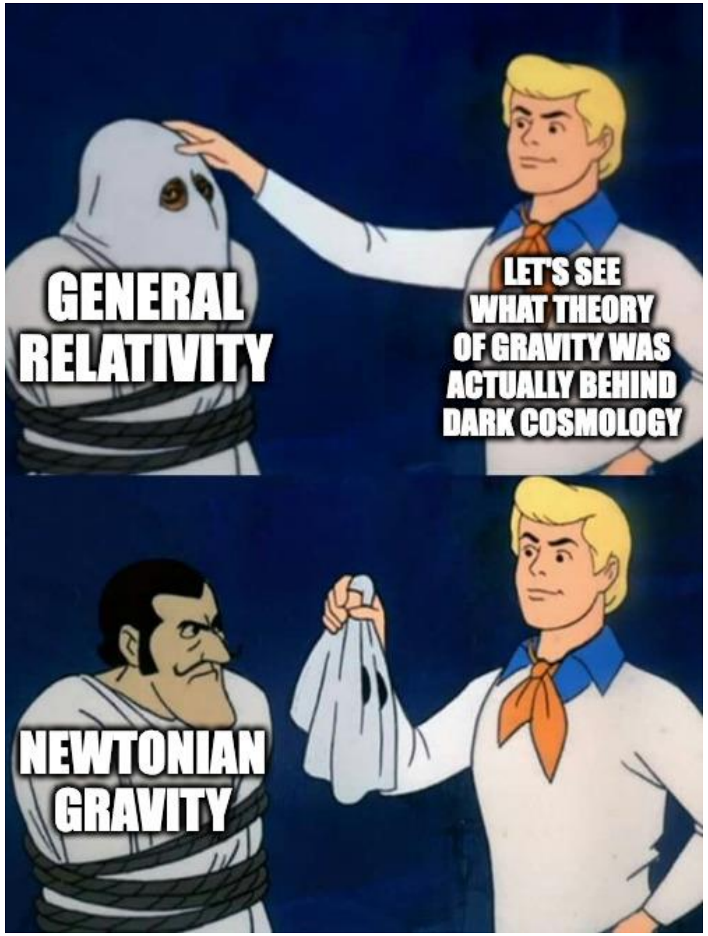
Circular reasoning in search of the cosmic rest frame?

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



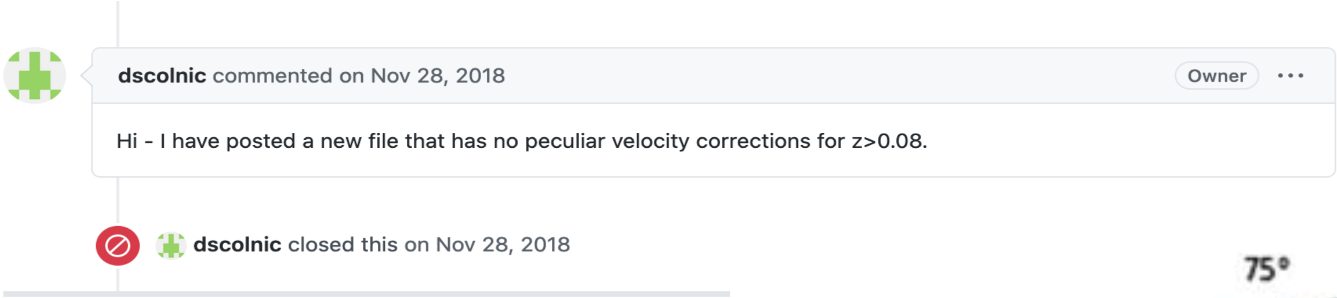
Infers the peculiar velocity field from a density contrast field derived from data (2M++ compilation) using linear Newtonian perturbation theory.

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



Carrick, Turnbull, Lavaux, Hudson *MNRAS*, 450 (2015) 317

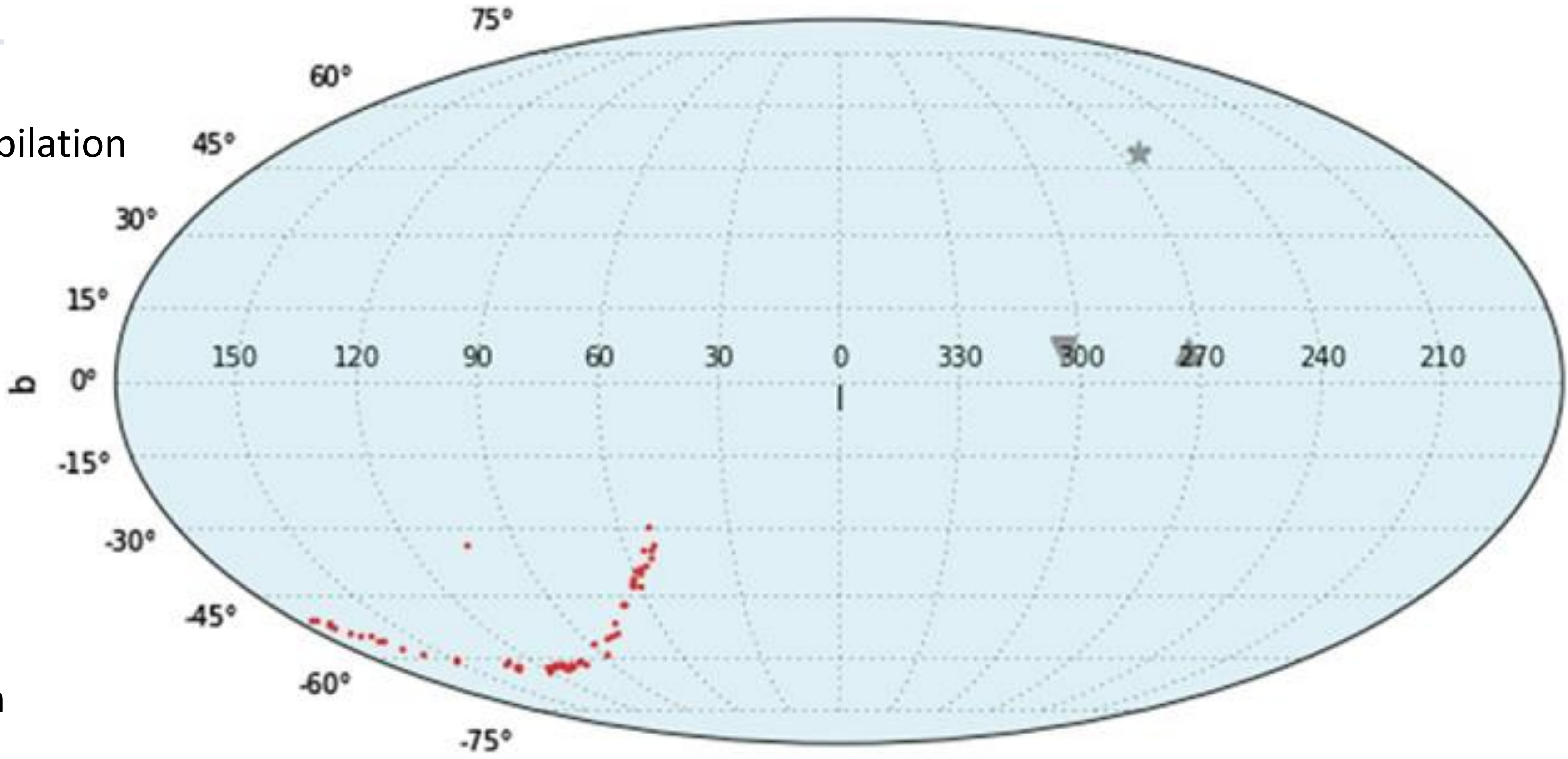
"We find that an external bulk flow is preferred at the 5.1σ level, and the best fit has a velocity of 159 ± 23 km s^{-1} towards *l* = 304° ± 11°, *b* = 6° ± 13°" [beyond 200 h^{-1} Mpc radius]


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

Also in the intermediate Pantheon compilation



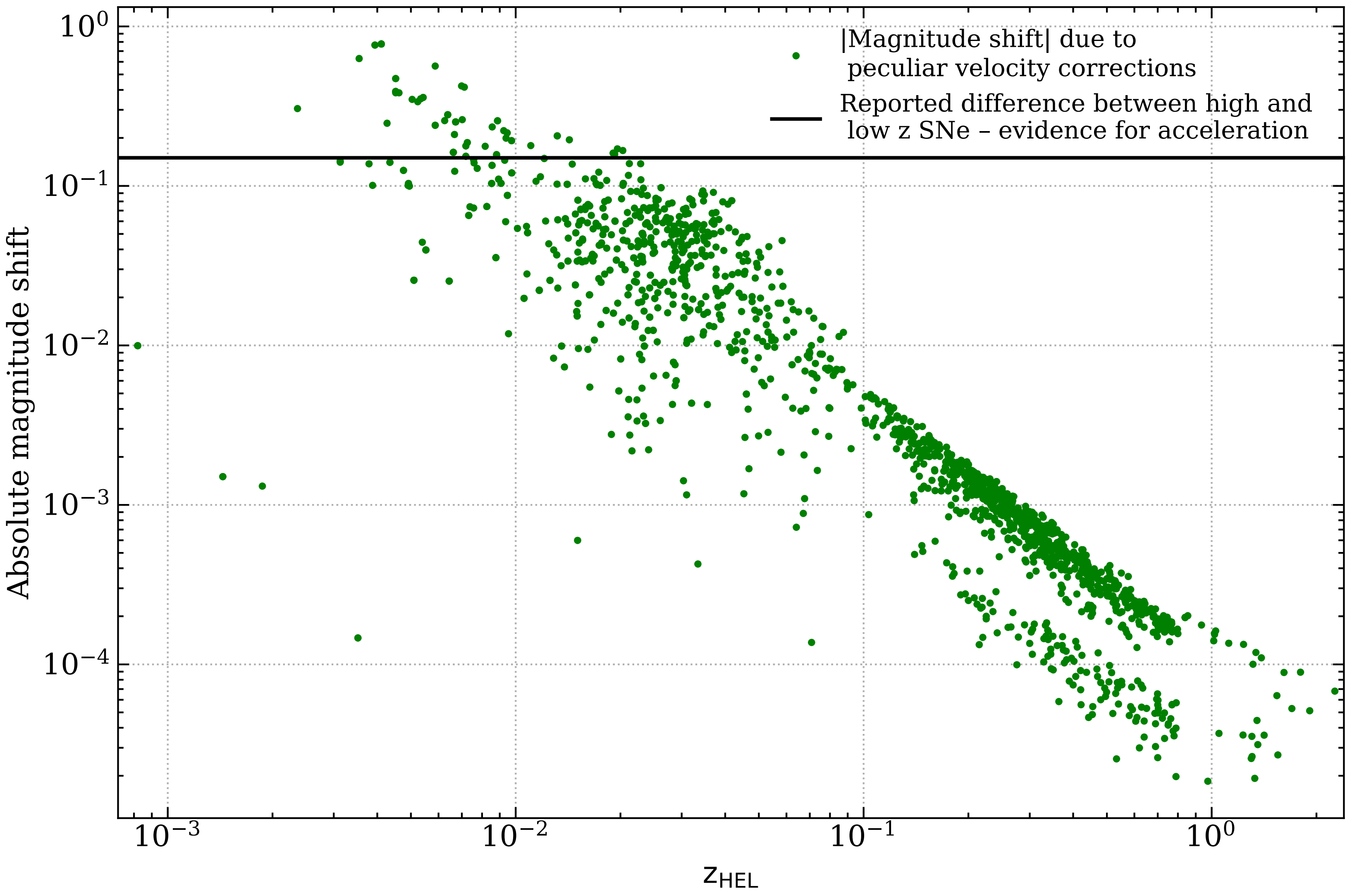
https://github.com/dscolnic/Pantheon

1905.00221

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

Each one of the supernovae now has to be corrected

The corrections applied to the low *z* ones are far larger than the 0.15 mag relative dimming between low z and high *z* SNe



How to sculpt an elephant?

Dipole Cosmology: The Copernican Paradigm Beyond FLRW

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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

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)

Large-scale geometry of the Universe

Yassir Awwad♠ and Tomislav Prokopec♢

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

Spatially Homogeneous Universes with Late-Time Anisotropy

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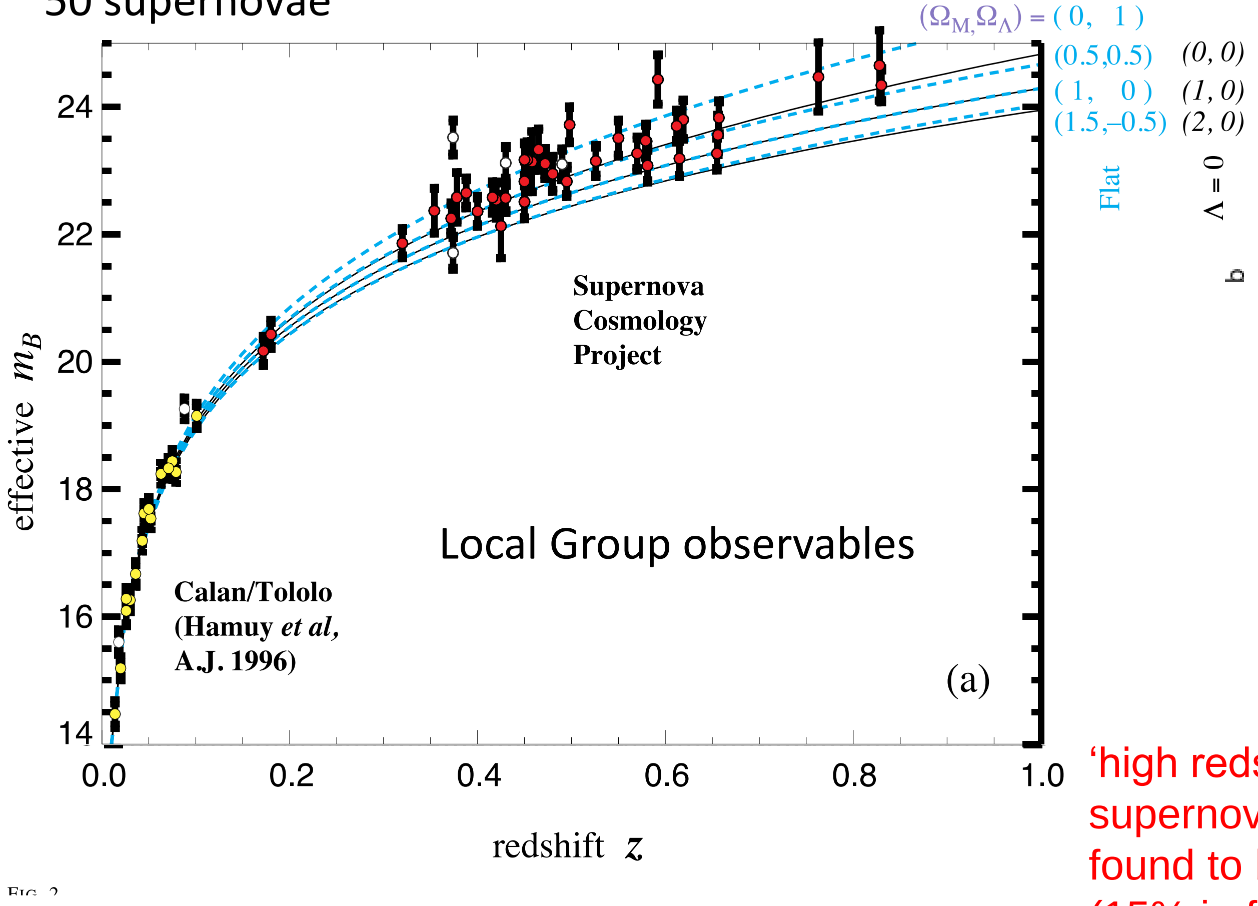
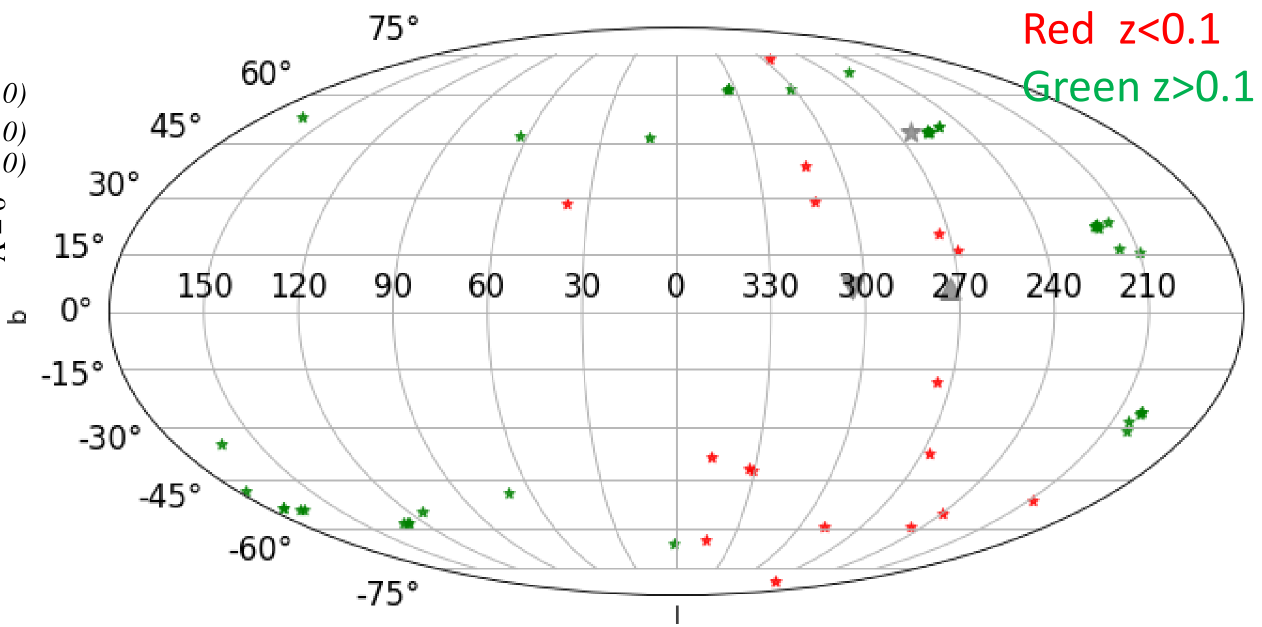
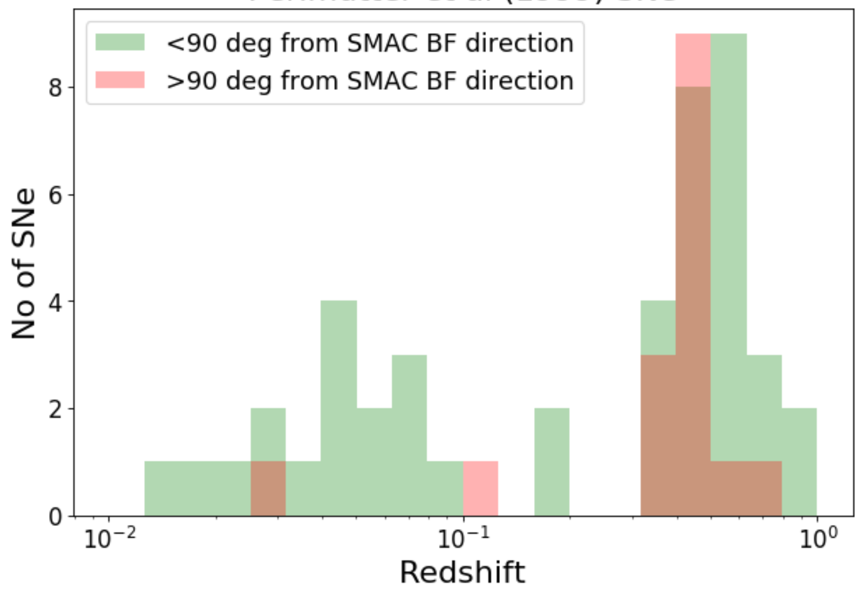
The discovery of dark energy

~50 supernovae



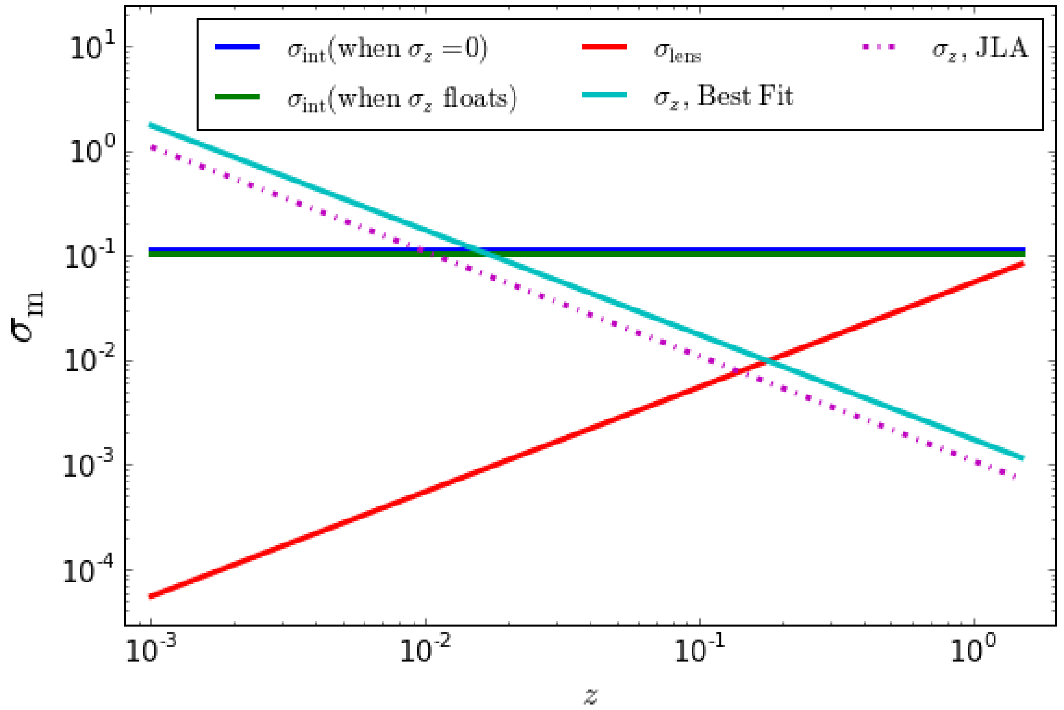


Perlmutter et al (1999) SNe



'high redshift supernovae were found to be dimmer (15% in flux) than the low redshift supernovae (compared to what would be expected in a $\Lambda = 0$ universe)'

Collaboration	Number of SNe Ia	N_{out}	Lightcurve	CRF	Treatment of peculiar velocities	Lensing
SCP [9]	60 (18+42)	4	"stretch"	LG	$\sigma_v = 300$ km s^{-1}	
HZT [10]	50 (34+16)	-	MLCS, template	CMB	$\sigma_v = 200$ km s^{-1}, 2500 km s^{-1} at high z	
SNLS [68]	117 (44+73)	2^a	SALT	CMB+helio	$z_{min} = 0.015$	
SCP (Union) [69]	307	8^a	SALT	CMB+helio	$z_{min} = 0.015$, $\sigma_v = 300$ km s^{-1}	$\sigma^l = 0.093z$
Union2 [70]	557	12^a	SALT2	CMB+helio	$z_{min} = 0.015$, $\sigma_v = 300$ km s^{-1}	$\sigma^l = 0.093z$
SCP [72]	580	0	SALT2	CMB+helio	not available	corrections
SNLS [71]	472	6^a	SALT2 & SiFTO	CMB	$\sigma_v = 150$ km s^{-1} + SN-by-SN corrections	$\sigma^l = 0.055z$
JLA [11]	740	0	SALT2	CMB	$\sigma_v = 150$ km s^{-1} + SN-by-SN corrections	$\sigma^l = 0.055z$
Pantheon [62]	1048	86	SALT2	CMB	$\sigma_v = 250$ km s^{-1} + SN-by-SN corrections	$\sigma^l = 0.055z$



Newest : Union 3, data not properly public yet

Mohayaee et al 2021 *Eur.Phys.J.ST* 230 (2021) 9

Some worry about the scale of Λ

General Relativity

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

"Space tells matter how to move
Matter tells space how to curve": Wheeler

No special (inertial or accelerating) frames

A problem in Riemannian geometry.

FLRW Exact Solution
Exact isotropy and homogeneity **at all scales:**

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

Synchronized clocks, a constant time hypersurface

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2$$

$$H^2 = H_0^2 [\ \Omega_M (1+z)^3 + \Omega_K (1+z)^2 + \Omega_\Lambda]$$

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

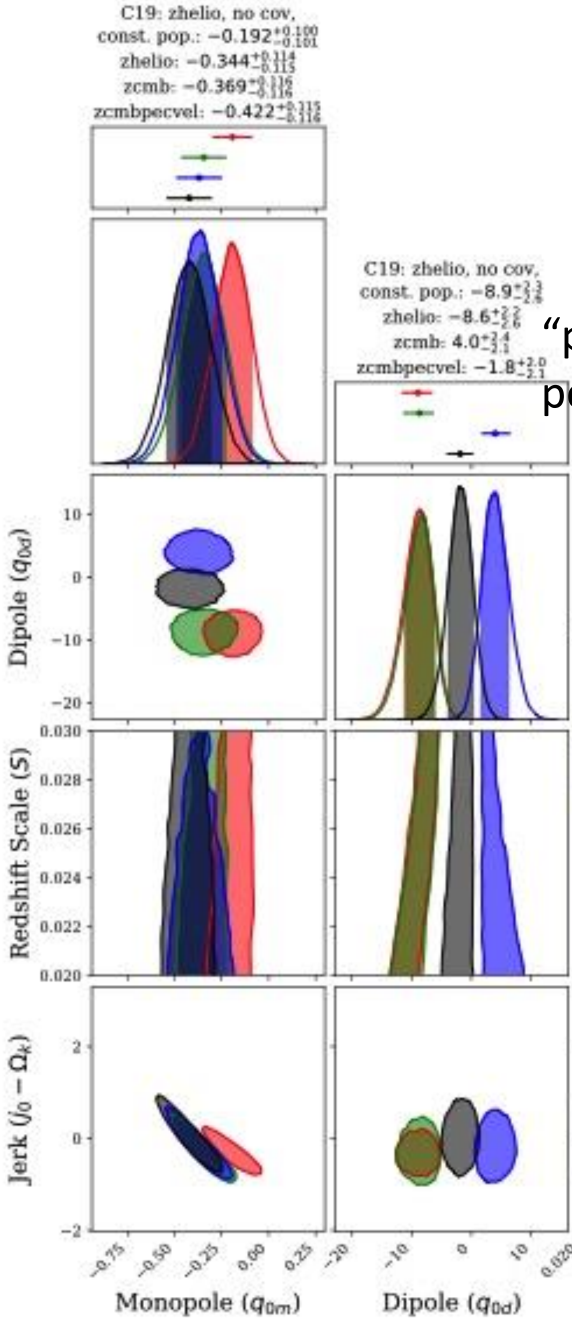
The cosmic sum rule

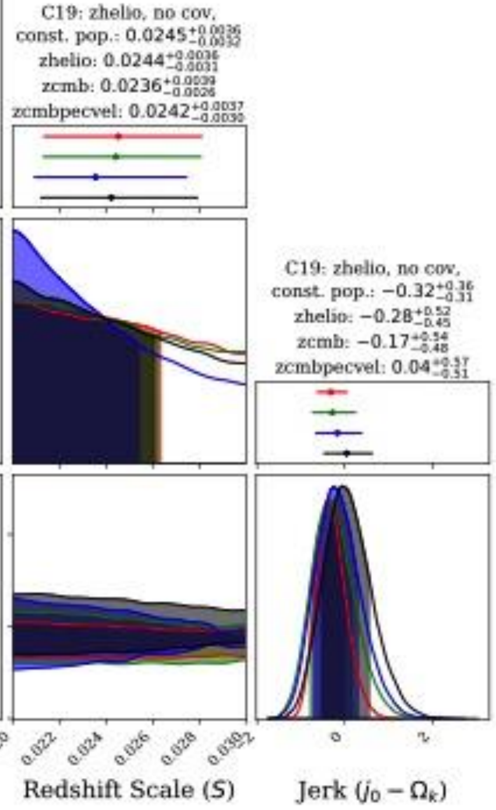
Λ, if it's a vacuum energy appears to be about 10^{120} below its 'natural' value from QFT
"there is nonzero vacuum energy of *just the right order of magnitude to be detectable today*"   Is the evidence for dark energy secure?
Sarkar, Gen.Rel.Grav.40:269-284,2008

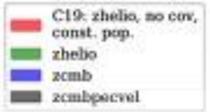
Rubin & Heitlauf 2019

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

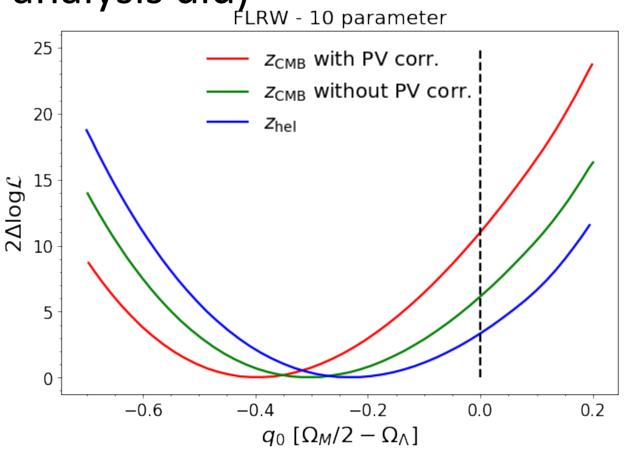
"plus corrections for **known** peculiar velocities (as the JLA analysis did)"

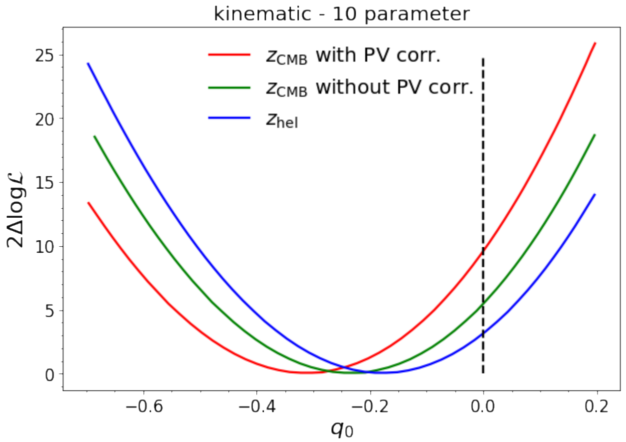


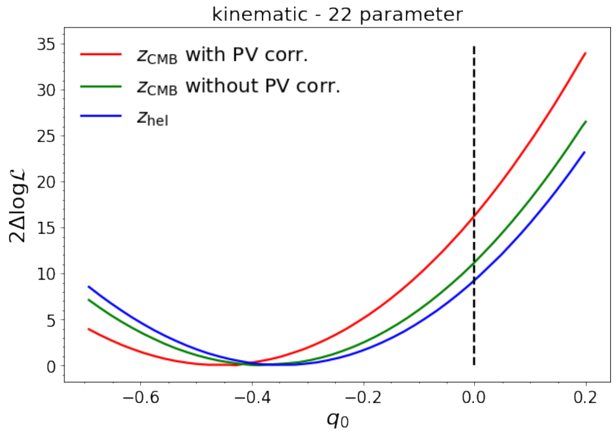




Our Response







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

Peculiar velocity impact on SN1a magnitude

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

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

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

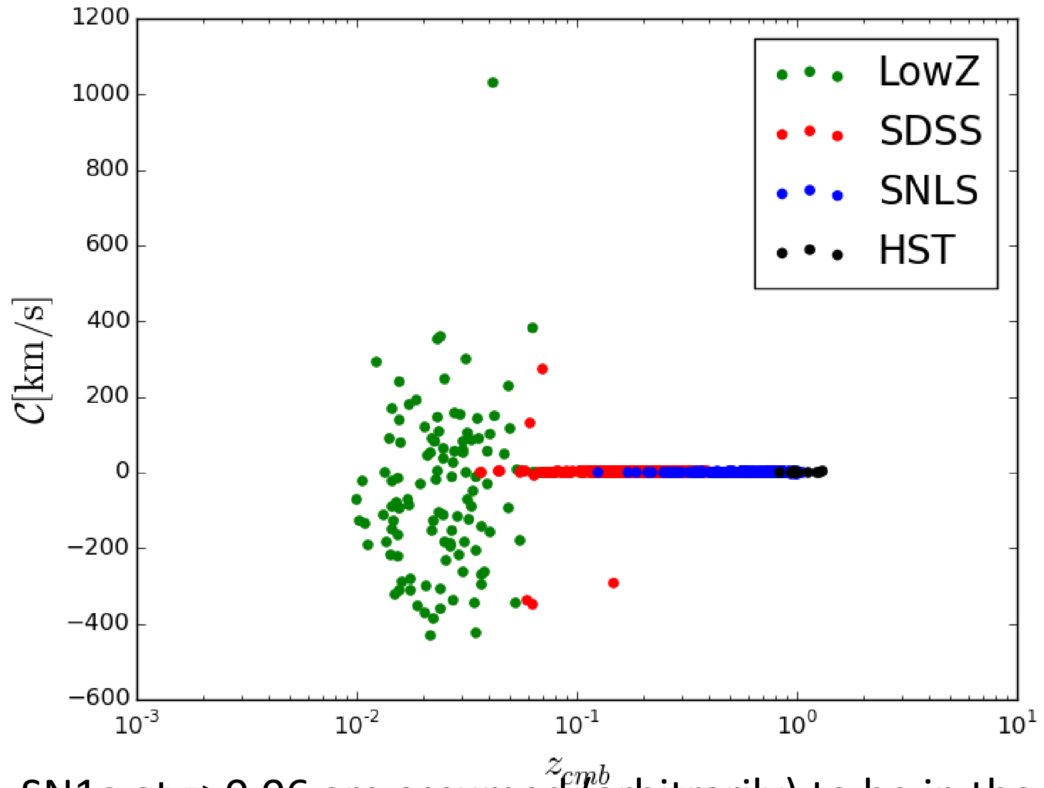
JLA (and Pantheon) redshifts and magnitudes have been 'corrected' to account for the local bulk flow.

```
#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

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

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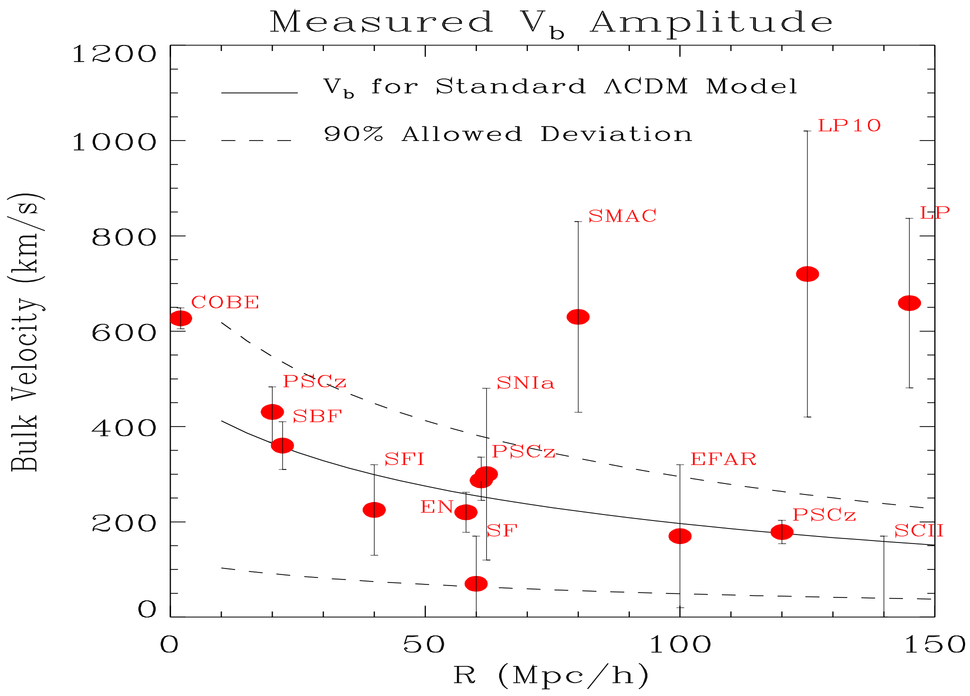

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03D1fc 0.330932 0.332000 0 21.861412 0.086437
03D1fq 0.798566 0.800000 0 24.510389 0.101777
```

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

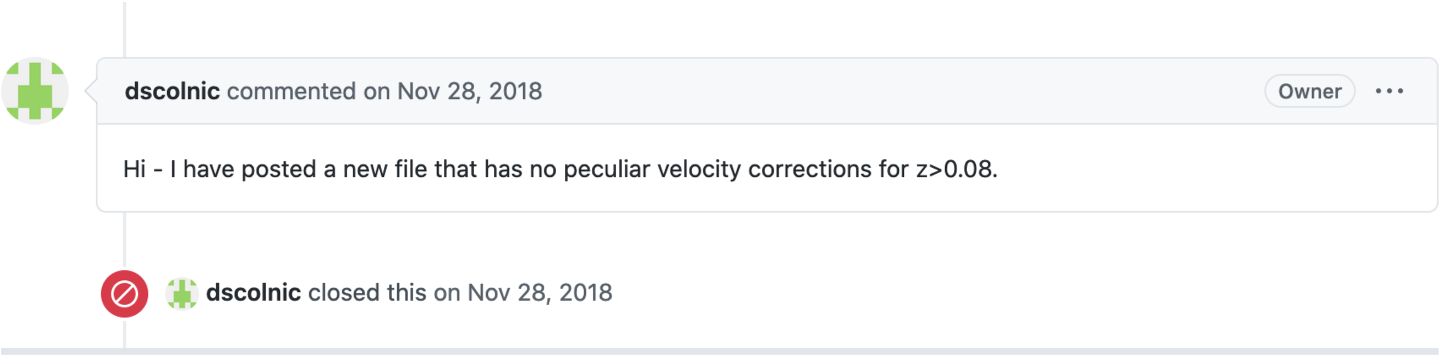
$z_{hel} \rightarrow measured$

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

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

There is an arbitrary discontinuity within the data.

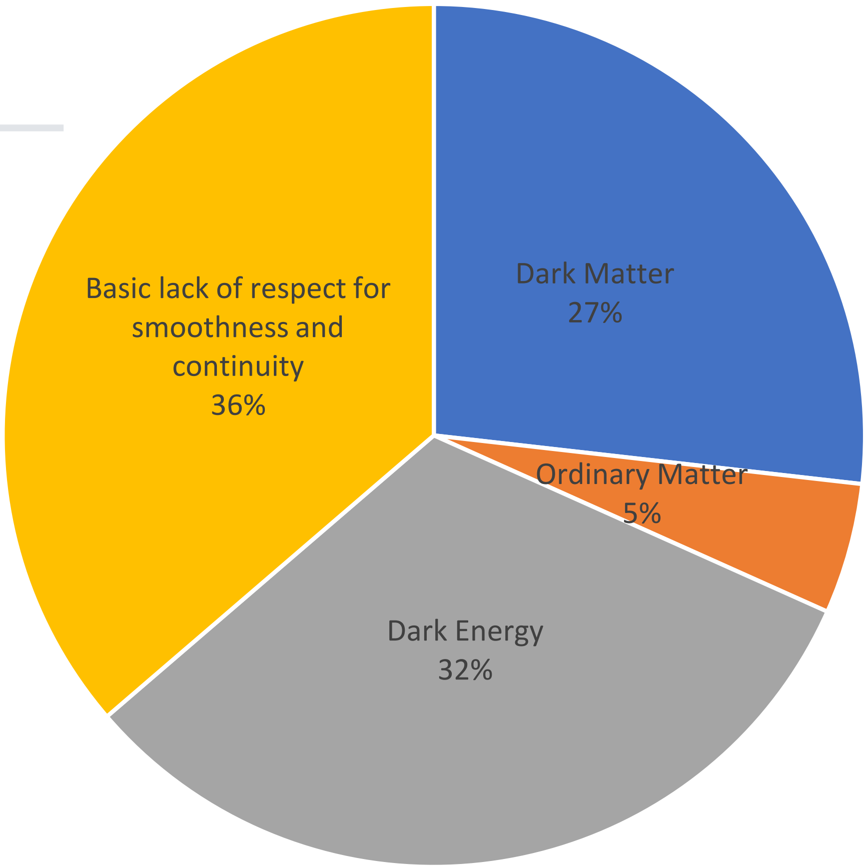
Also in the subsequent Pantheon compilation

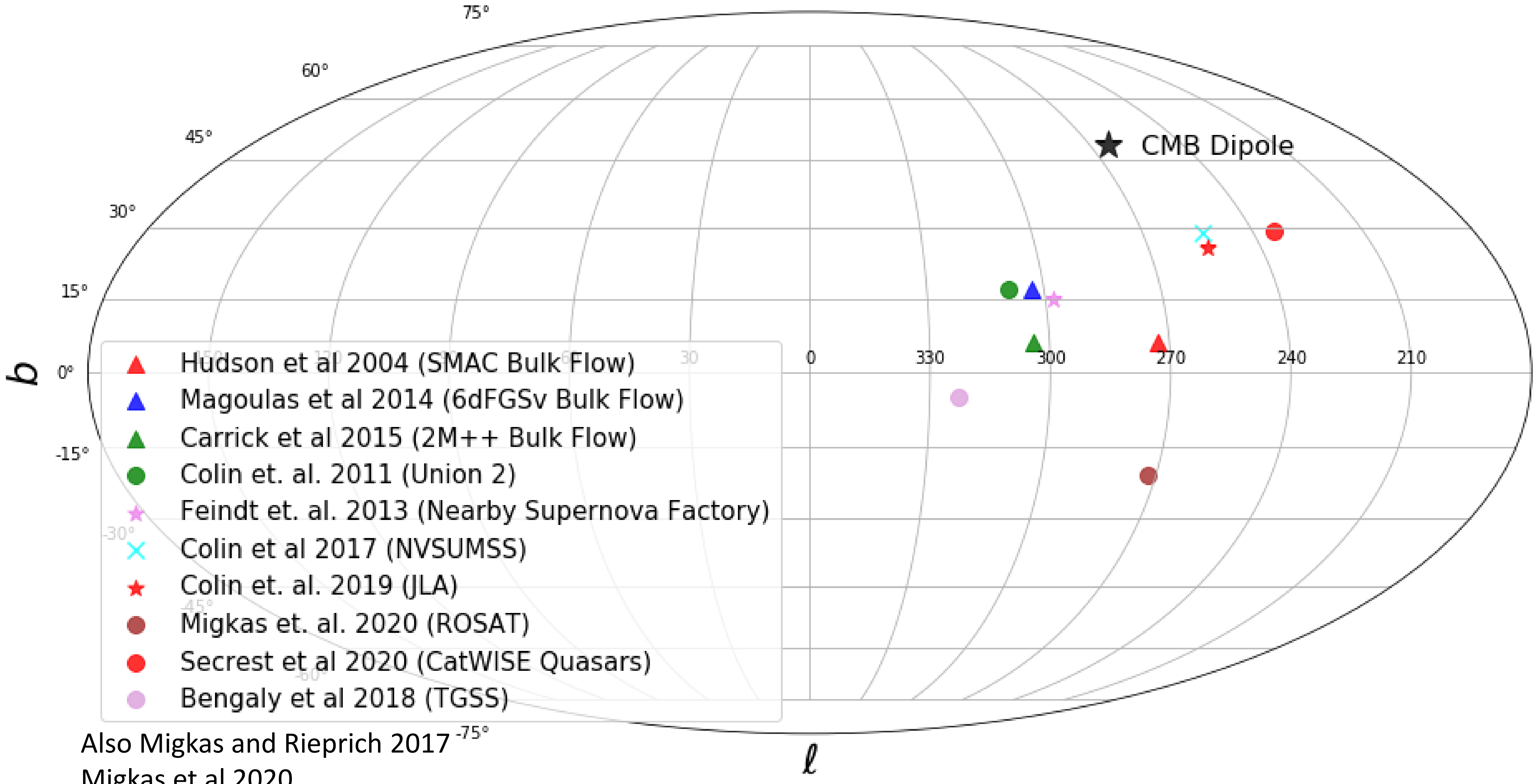


https://github.com/dscolnic/Pantheon/issues/2

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

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

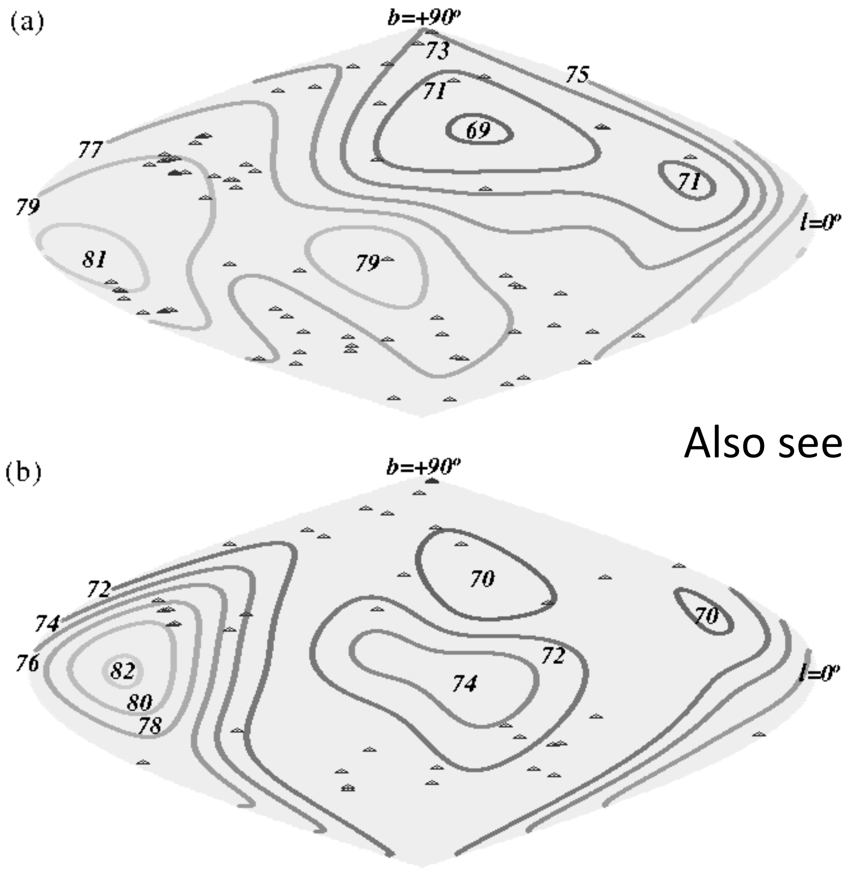
Ellis, "On the Raychaudhury Equation"
Pramana–J.Phys.,Vol. 69, No. 1, July 2007

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

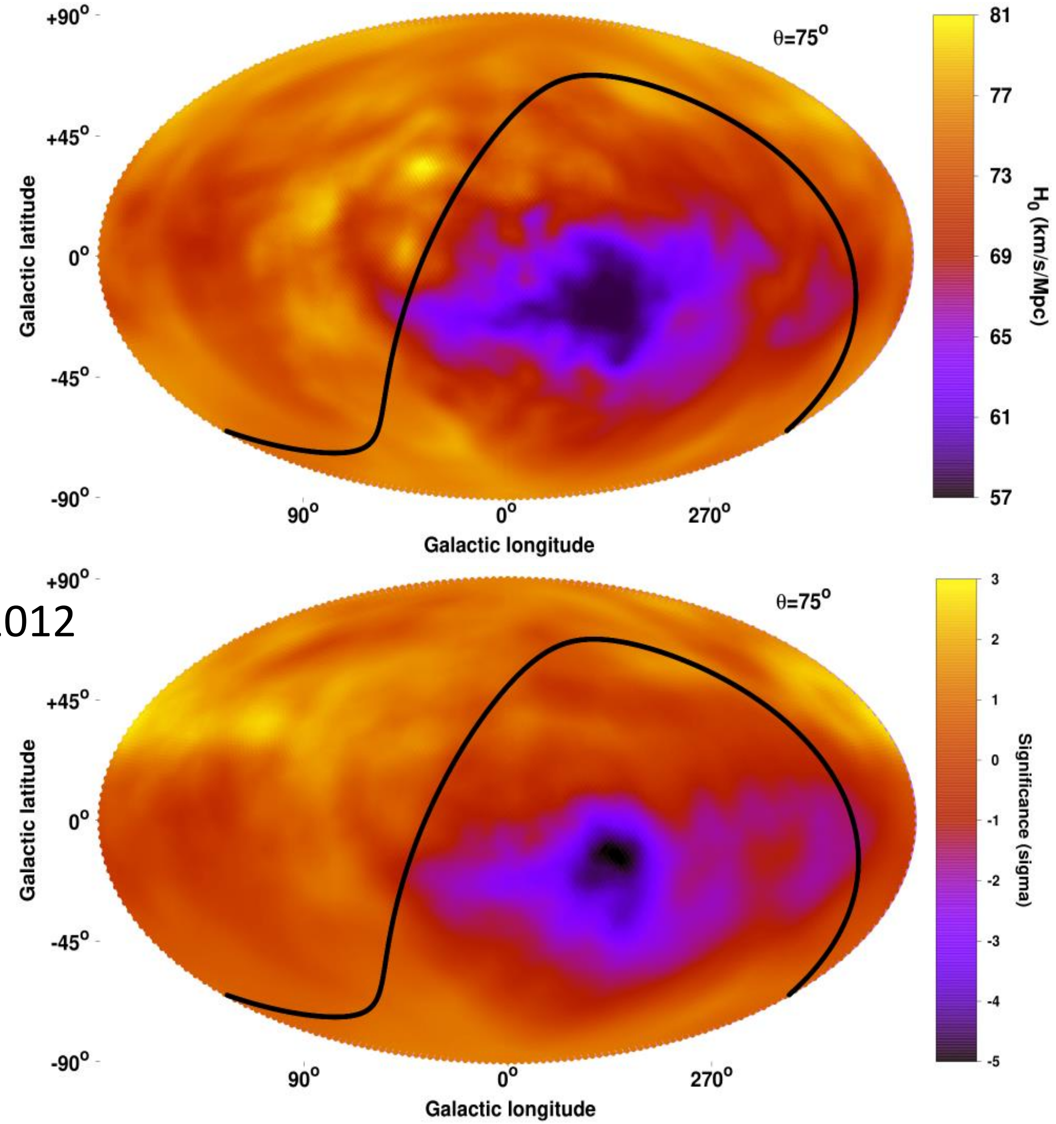
Some existing debates in literature (inhomogeneous cosmology/backreactions) suggest that problems such as Dark Matter and Dark Energy can also be tackled be critically examining the tools and framework with which we do cosmology.

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.

The ‘fitting problem’ in cosmology

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.

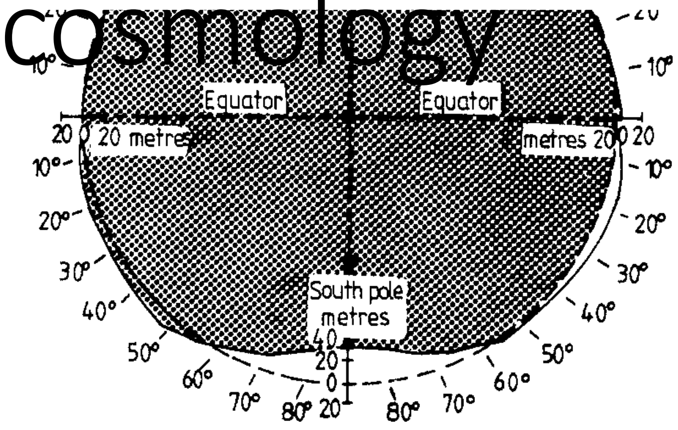
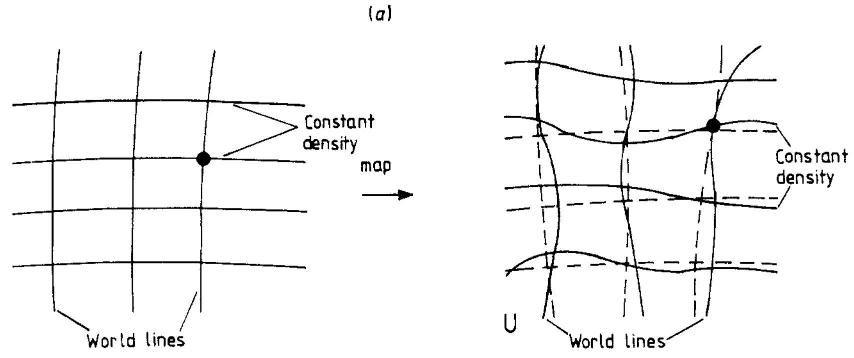


Figure 1. (*a*) An exactly uniform and spherically symmetrical FLRW universe U′ mapped into the lumpy universe U so as to give the best fit possible. (*b*) An exactly spherical sphere fitted to the lumpy world to give the best fit possible.

ion

mology aims at finding the large-scale matter distribution and spacetime the universe from astronomical observations. There are broadly speaking approaches that have been applied to this problem.

The ‘fitting problem’ in cosmology 1699



Section 4.3 and 4.4 give a detailed discussion of how to correct for peculiar velocities, isotropize data, fit it to an idealized model, judge goodness of fit and what it means for fundamental physics
Read this along with Conley et al 2011, Rubin & Heitlauf 2019 and Davis et al 2011

Results

Table 2. Tilted local universe, with σ_z set to zero, fitted to data with the MLE.

	$-2\log\mathcal{L}_{\max}$	q_m	q_d	S	$j_0-\Omega_k$	α	$x_{1,0}$	$\sigma_{x_{1,0}}$	β	c_0	σ_{c_0}	M_0	σ_{M_0}
Tilted universe	−208.28	−0.157	−8.03	0.0262	−0.489	0.135	0.0394	0.931	3.00	−0.0155	0.071	−19.027	0.114
No tilt (q_d = 0)	−189.52	−0.166	0	–	−0.460	0.133	0.0396	0.931	2.99	−0.014	0.071	−19.028	0.117
No accn. (q_m = 0)	−205.98	0	−6.84	0.0384	−0.836	0.134	0.0365	0.931	2.99	−0.014	0.071	−19.002	0.115

Notes. The BIC for the models above is −129.00, −123.45, and −133.31, providing strong evidence for the last model.

Table 3. Tilted local universe, with σ_z left floating, fitted to data with the MLE.

	$-2\log\mathcal{L}_{\max}$	q_m	q_d	S	$j_0-\Omega_k$	α	$x_{1,0}$	$\sigma_{x_{1,0}}$	β	c_0	σ_{c_0}	M_0	σ_{M_0}	$c\sigma_z$ [km s^{-1}]
Tilted universe	−216.90	−0.154	−6.33	0.0305	−0.497	0.134	0.0395	0.932	3.04	−0.0158	0.071	−19.022	0.106	241
No tilt (q_d = 0)	−203.23	−0.187	0	–	−0.425	0.133	0.0398	0.932	3.05	−0.0151	0.071	−19.032	0.106	274
No accn. (q_m = 0)	−214.74	0	−5.60	0.0350	−0.833	0.133	0.0368	0.932	3.04	−0.0145	0.071	−19.000	0.106	243

Notes. The BIC for the models above is −131.01, −130.55, and −135.46, providing positive evidence for the last model.

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

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

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

Results

$q_d >> q_m$

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No tilt ($q_d = 0$)	−203.23	−0.187	0	–	−0.425	0.133	0.0398	0.932	3.05	−0.0151	[illegible]
No accn. ($q_m = 0$)	−214.74	0	−5.60	0.0350	−0.833	0.133	0.0368	0.932	3.04	−0.0145	[illegible]

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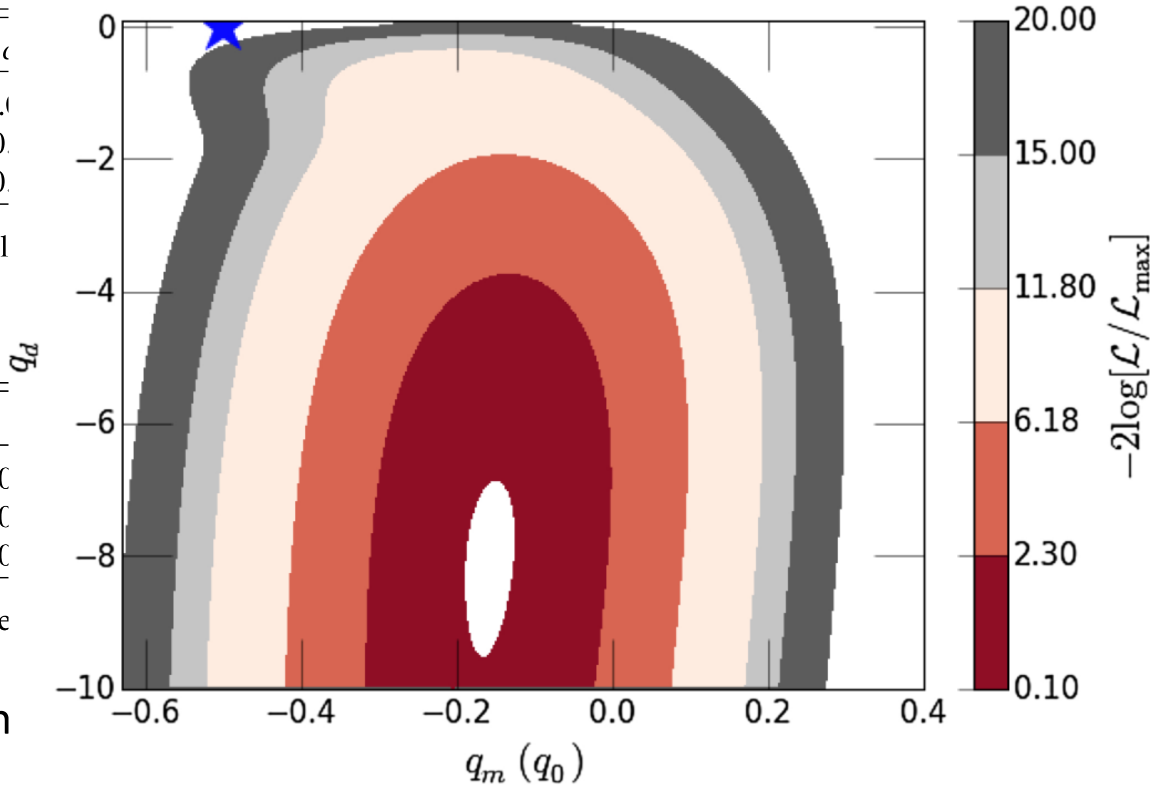

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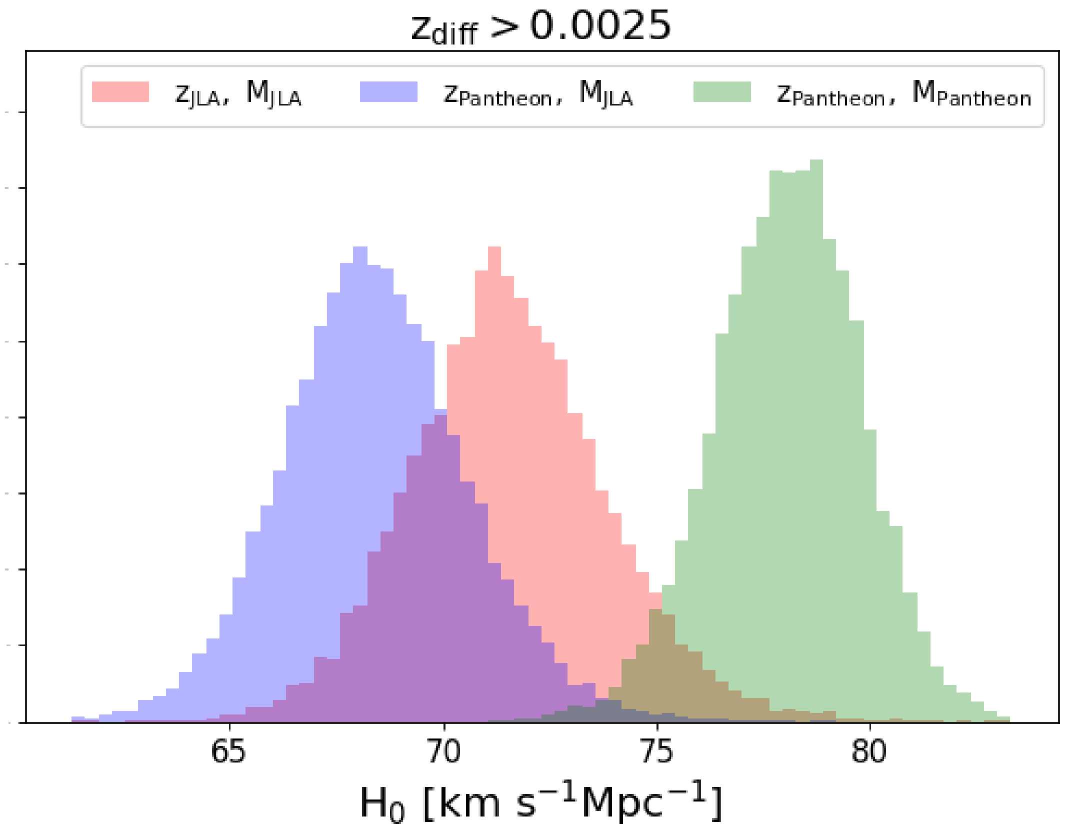
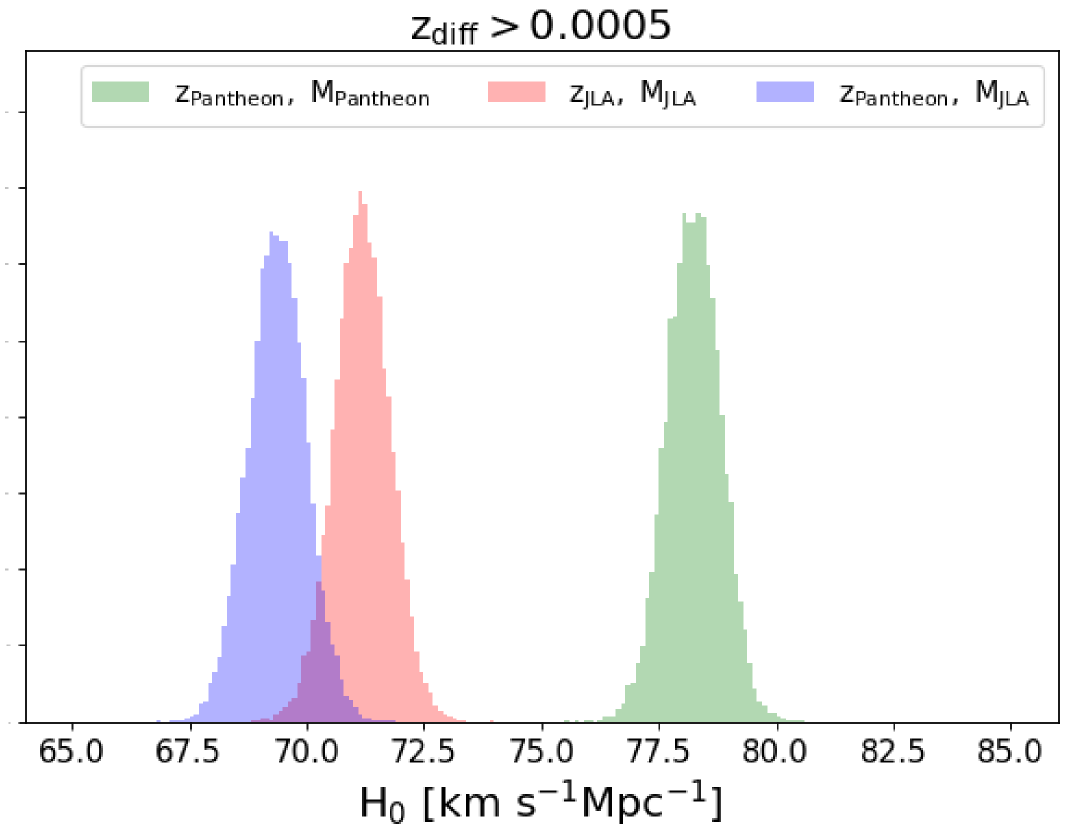
Cosmic acceleration may simply be an artefact of our being located inside a ‘bulk flow’!

A trivial solution to the Hubble tension?





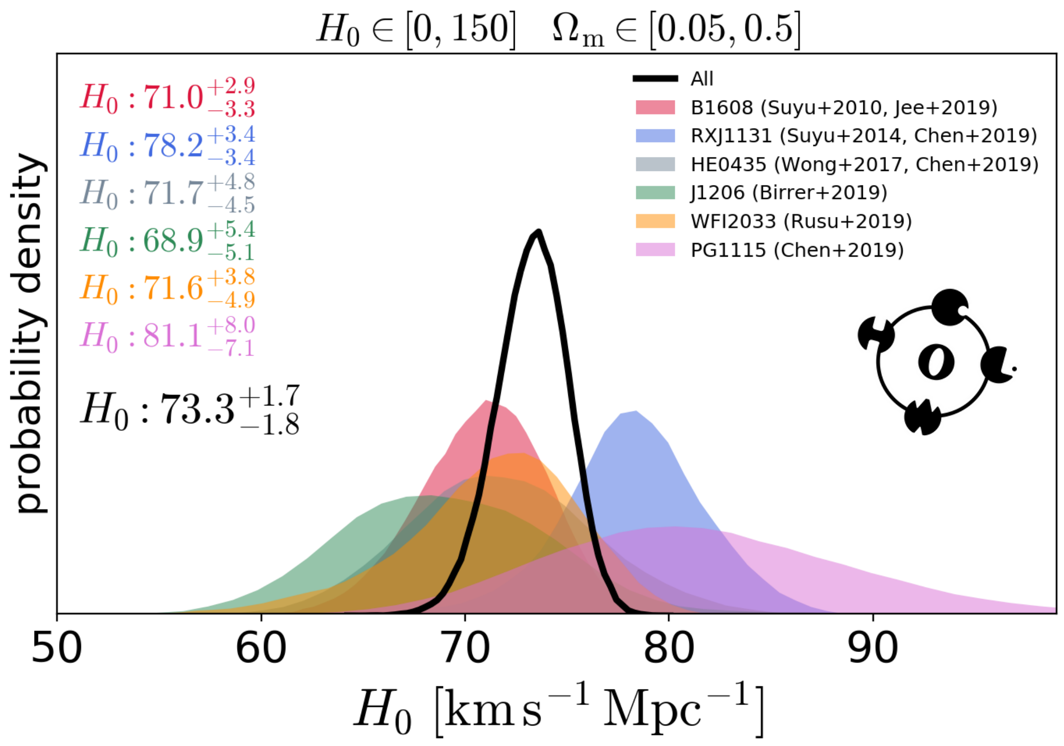
The shifts in redshift and magnitude appear to be sufficient to lower the Hubble 'constant' from ~72 to 68, keeping many other parameters fixed to that of Riess et al 2016

What is ΛCDM cosmology?

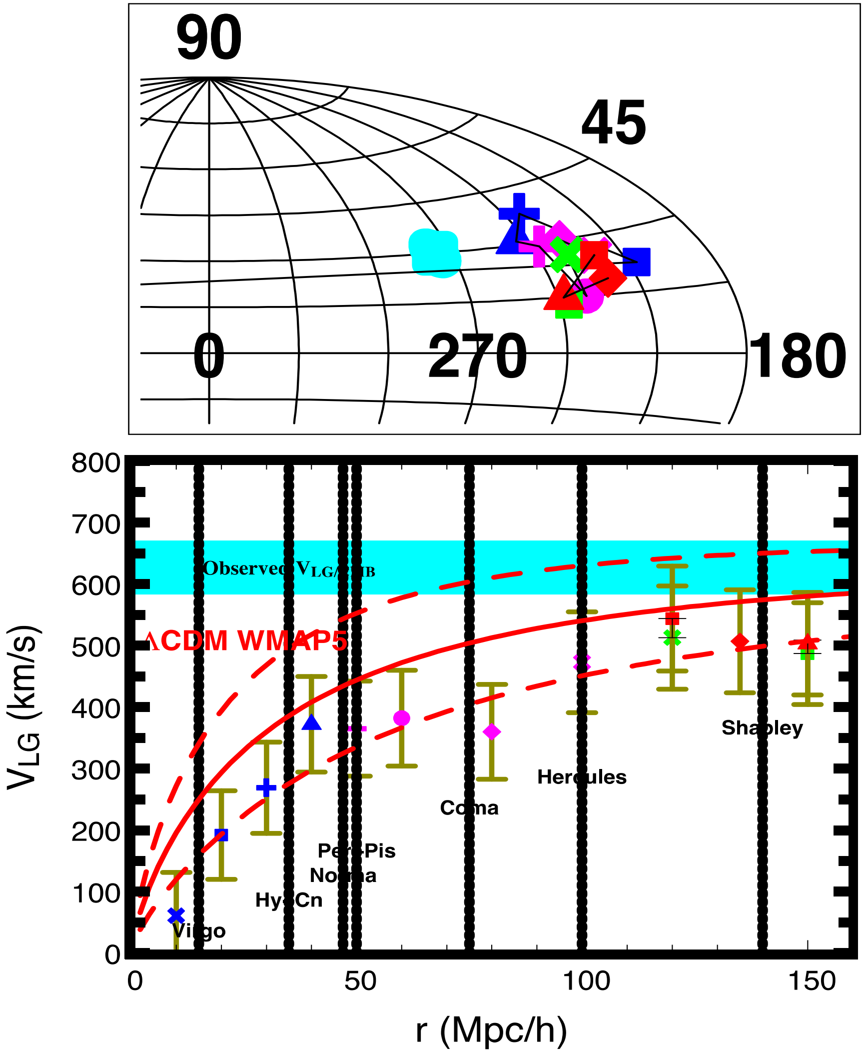
The naive fitting of data from the real Lumpy Universe, to a smooth toy model, treating all scatter as statistical, when it could be cosmological

Such as this H0licow measuement

Note : This is very honestly communicated

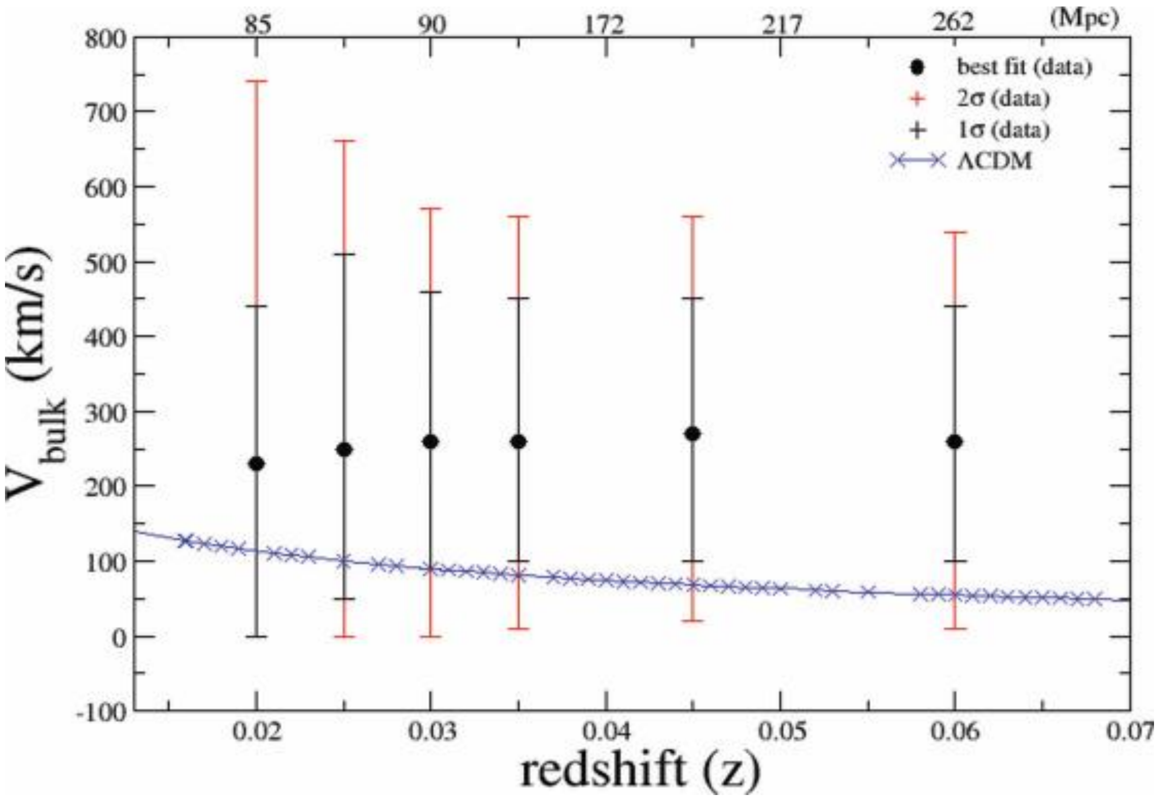


Where is the cosmic ‘rest frame’?



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

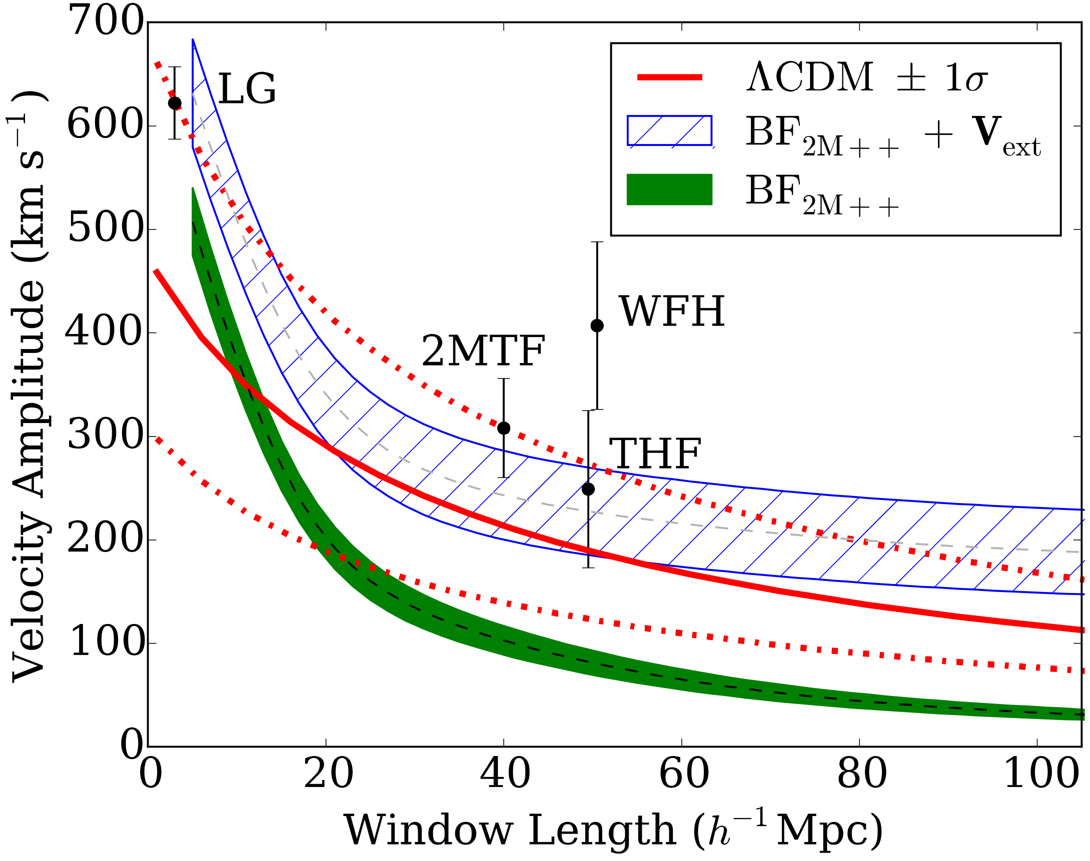
•*Astrophys.J.* 709 (2010) 483-498

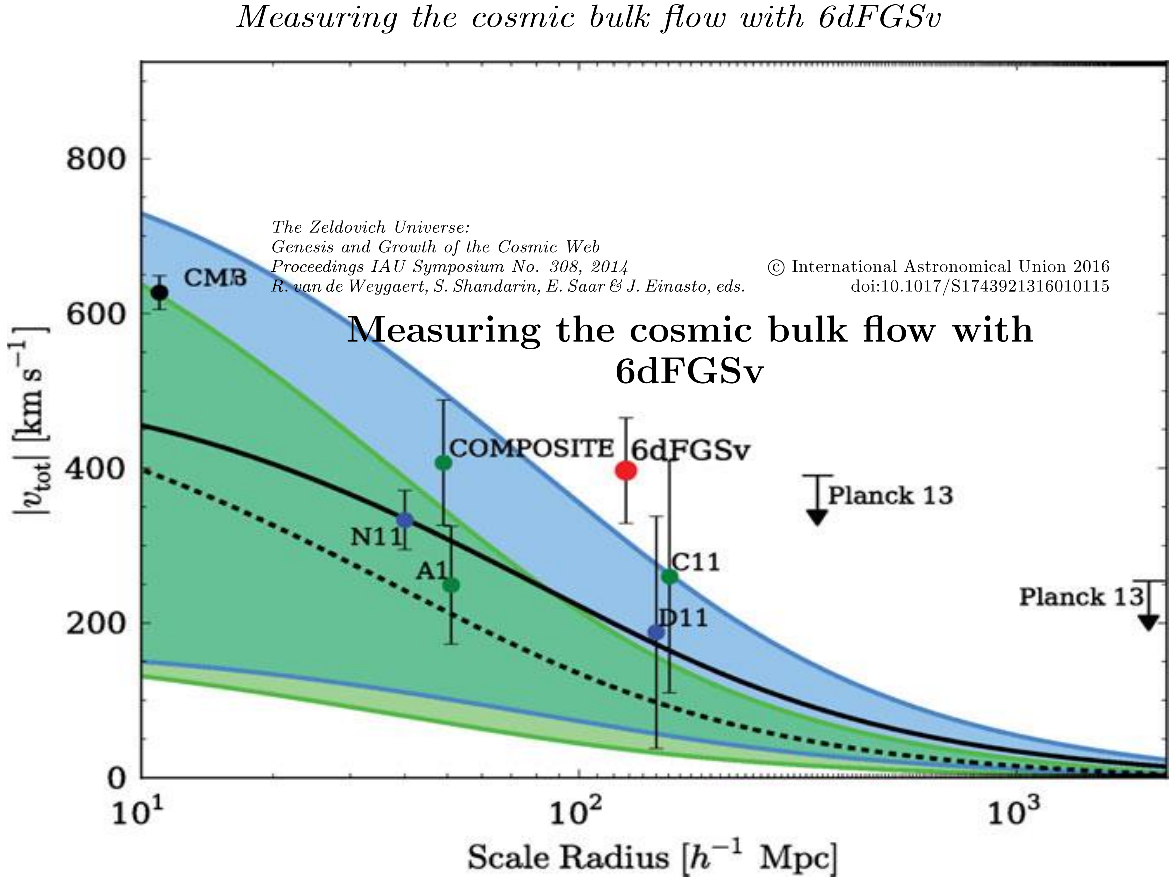


Colin J., Mohayaee R., Sarkar S. & Shafieloo A., 2011, MNRAS, 414, 264

Confirmed by Feindt et al

Where is the cosmic 'rest frame'?





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 300 Mpc radius]

Magoulas et al, 2014

Springbob et al 2014

But the real Universe has structure on all scales

The FLRW universe

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

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}

We can observe only one.

The Real Universe has structure on much smaller scales than our representations of it

Standard Cosmology

N body simulations assume the existence of a background FLRW metric and use Newtonian gravity (which is the zero velocity weak field of GR).

Linearizations, perturbation theory, initial conditions from inflation

Peculiar velocities are things moving w.r.t. a FLRW background

Defended by authors of GR textbooks such as Robert Wald, using heuristic arguments.

Inhomogeneous Cosmology

Real Universe can only be represented by an FLRW metric. Large scale dynamics obtained from the 'coarse graining' of small scale dynamics.

Is a complex system with nonlinear dynamics.

Peculiar velocities are differences in the expansion rate of the Universe

Has a true metric that is everywhere far from FLRW

Talks about almost flat, almost isotropic, almost FLRW cosmologies

Leading cosmologists, authors of textbooks such as Ellis and Kolb take this view.

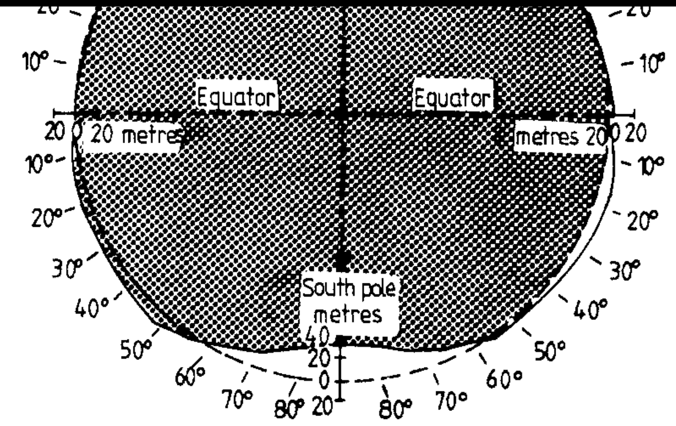
There is an averaging problem, a fitting problem and backreactions. Clarkson et al 2011 Rept.Prog.Phys. 74 (2011) 112901

The ‘fitting problem’ in cosmology

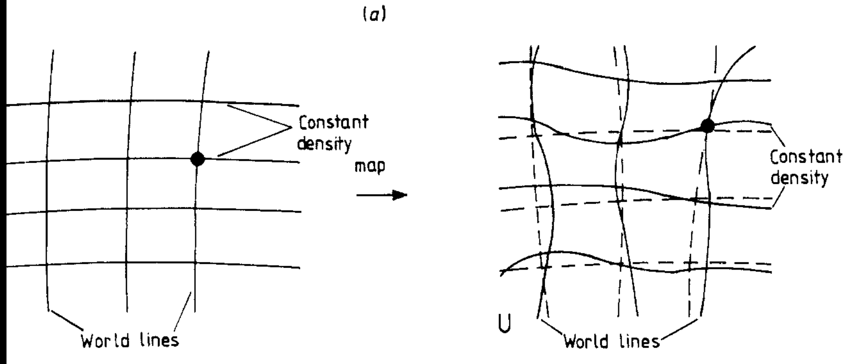
Abstract. This paper considers the best way to fit an idealised exactly homogeneous and isotropic universe model to a realistic (‘lumpy’) universe; whether made explicit or not, some such approach of necessity underlies the use of the standard Robertson–Walker models as models of the real universe. Approaches 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.

ion

mology aims at finding the large-scale matter distribution and spacetime the universe from astronomical observations. There are broadly speaking approaches that have been applied to this problem.



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



Section 4.3 and 4.4 give a detailed discussion of how to correct for peculiar velocities, isotropize data, fit it to an idealized model, judge goodness of fit and what it means for fundamental physics

Test this with a sample of 740 Type 1a Supernovae

Table 2. Tilted local universe, with σ_z set to zero, fitted to data with the MLE.

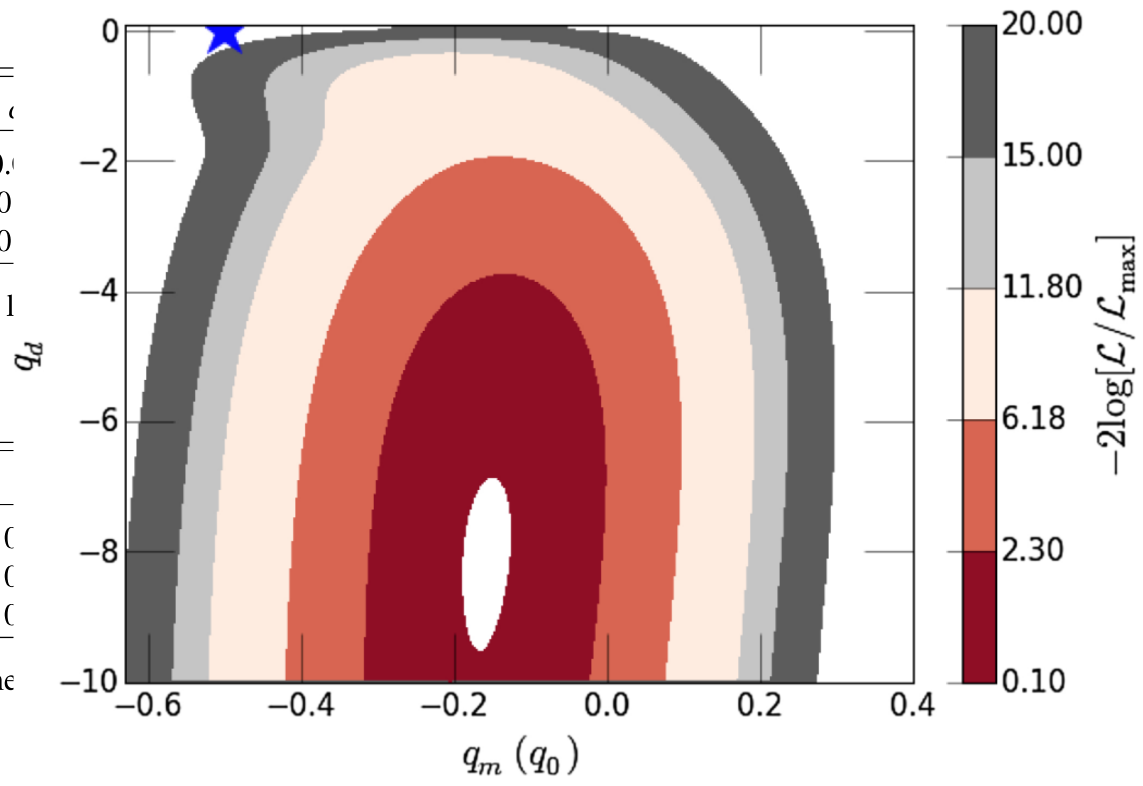
	$-2\log\mathcal{L}_{\rm max}$	$q_{\rm m}$	$q_{\rm d}$	S	$j_0-\Omega_k$	α	$x_{1,0}$	$\sigma_{x_{1,0}}$	β	c
Tilted universe	−208.28	−0.157	−8.03	0.0262	−0.489	0.135	0.0394	0.931	3.00	−0.
No tilt ($q_{\rm d}=0$)	−189.52	−0.166	0	–	−0.460	0.133	0.0396	0.931	2.99	−0
No accn. ($q_{\rm m}=0$)	−205.98	0	−6.84	0.0384	−0.836	0.134	0.0365	0.931	2.99	−0

Notes. The BIC for the models above is −129.00, −123.45, and −133.31, providing strong evidence for the l

Table 3. Tilted local universe, with σ_z left floating, fitted to data with the MLE.

	$-2\log\mathcal{L}_{\rm max}$	$q_{\rm m}$	$q_{\rm d}$	S	$j_0-\Omega_k$	α	$x_{1,0}$	$\sigma_{x_{1,0}}$	β	c_0	
Tilted universe	−216.90	−0.154	−6.33	0.0305	−0.497	0.134	0.0395	0.932	3.04	−0.0158	(
No tilt ($q_{\rm d}=0$)	−203.23	−0.187	0	–	−0.425	0.133	0.0398	0.932	3.05	−0.0151	(
No accn. ($q_{\rm m}=0$)	−214.74	0	−5.60	0.0350	−0.833	0.133	0.0368	0.932	3.04	−0.0145	(

Notes. The BIC for the models above is −131.01, −130.55, and −135.46, providing positive evidence for the



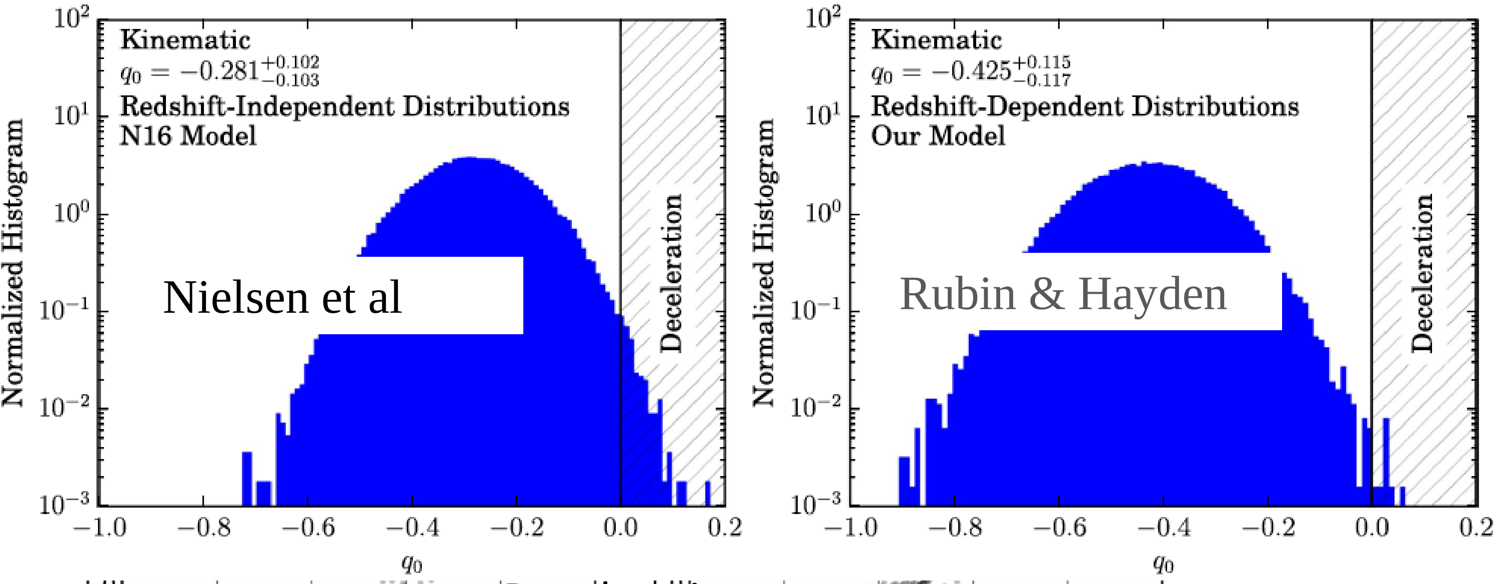
The dipolar component of q is larger than the monopole, and dominates out to z~0.1

$q_d >> q_m$

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

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

Rubin & Hayden (ApJ **833**:L30,2016) verify the results of Nielsen et al
but then argue that the light-curve fit parameters may be redshift-dependent



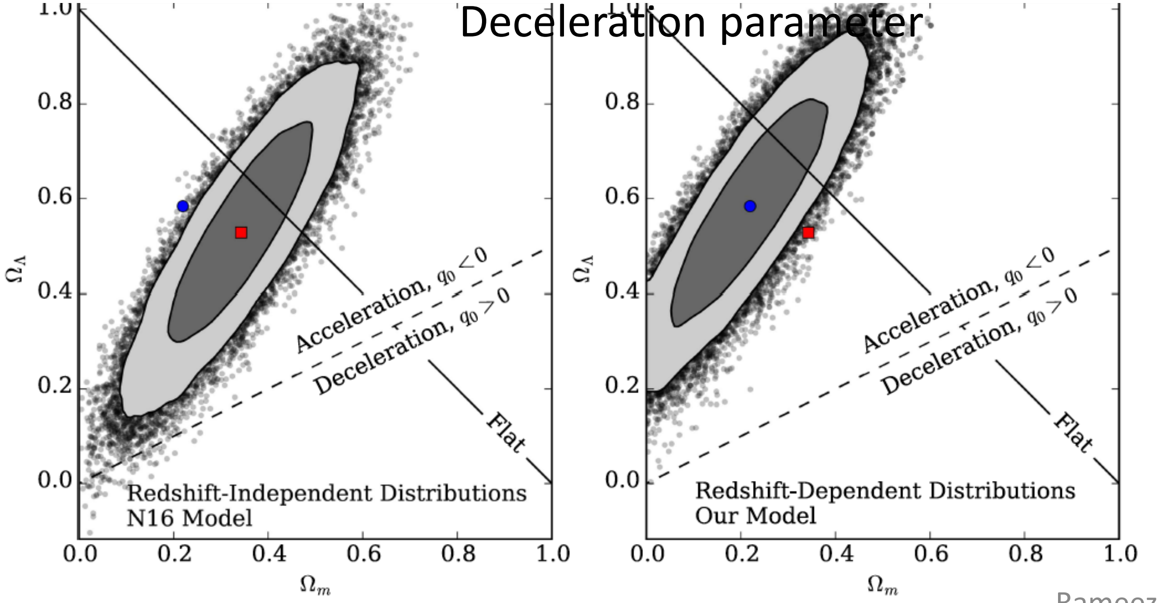


Figure 2. Ω_m–Ω_Λ constraints enclosing 68.3% and 95.4% of the samples from the posterior. Underneath, we plot all samples. The left panel shows the constraints obtained with x_1 and c distributions that are constant in redshift, as in the N16 analysis; the right panel shows the constraints from our model. The red square and blue circle show the location of the median of the samples from the respective posteriors.

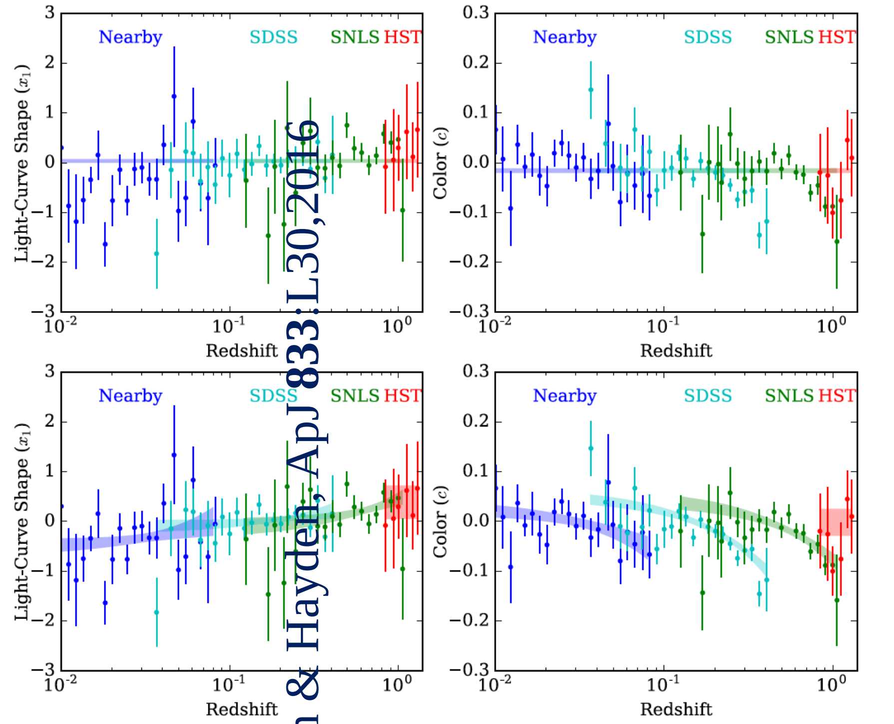


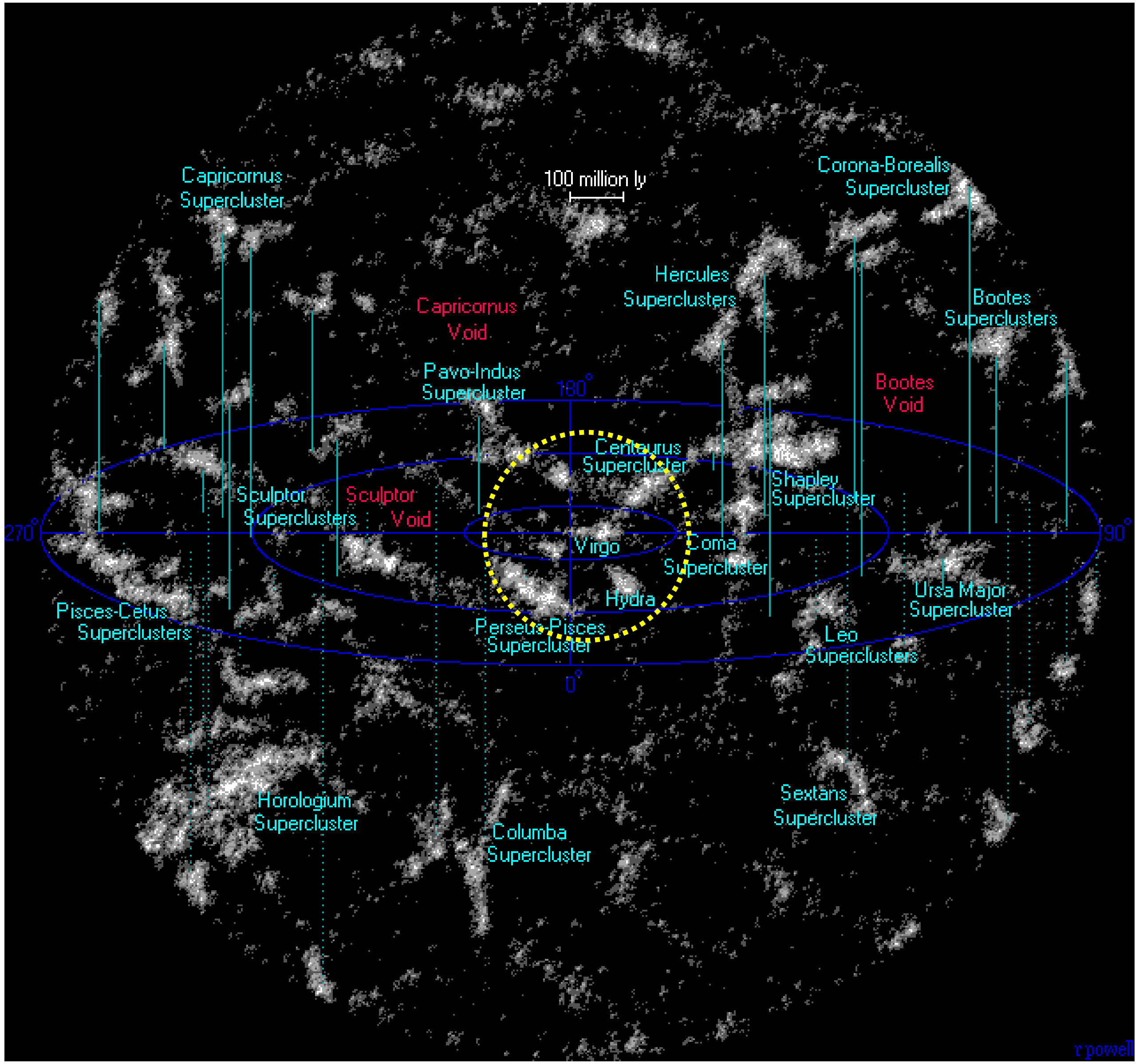
Figure 1. Binned x_1 (left panels) and c (right panels) light-curve parameters as a function of redshift for the JLA sample. The trend of color with redshift within each ground-based sample is expected due to the combination of the color-luminosity relation combined with redshift-dependent luminosity detection limits. The top panels show the 68% credible constraints on a constant-in-redshift model, as was used in N16. The bottom panels show our proposed revision. Failing to model the drift in the mean observed distributions demonstrated by the bottom panels will tend to cause high-redshift SNe to appear brighter on average, therefore reducing the significance of accelerating expansion.

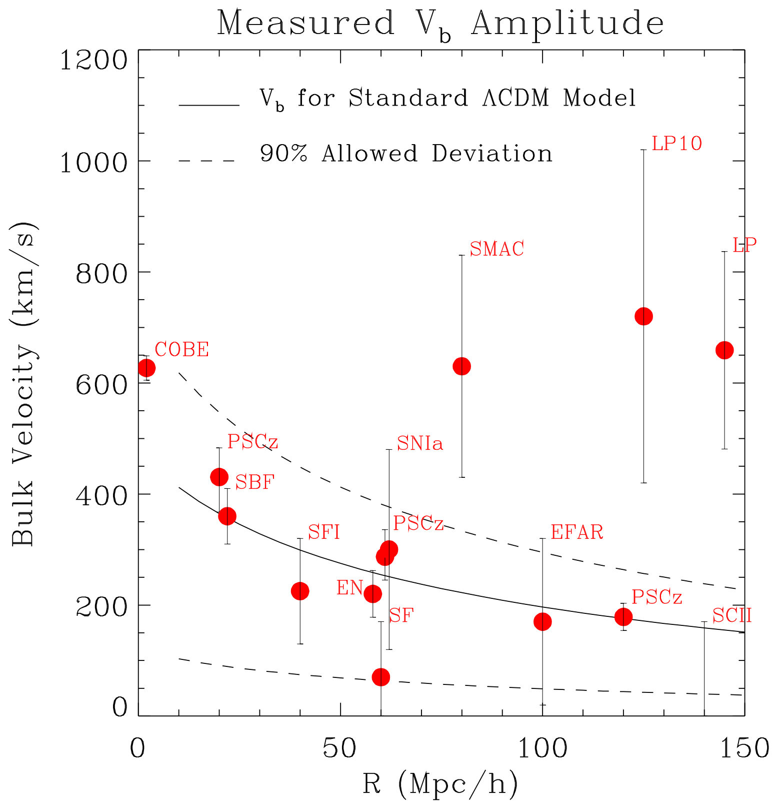
Two out of 3 parameters that go into the distance modulus have been examined by eye and made sample and redshift dependent.

Against the principles of blinded data analysis.

20 hyperparameters to standardize 740 SN1e

Even if this is justified, the significance with which a non-accelerating universe is rejected rises only to ≲4σ still inadequate to claim a 'discovery' (even though the dataset has increased from ~50 to 740 SNe Ia in 20 yrs)!

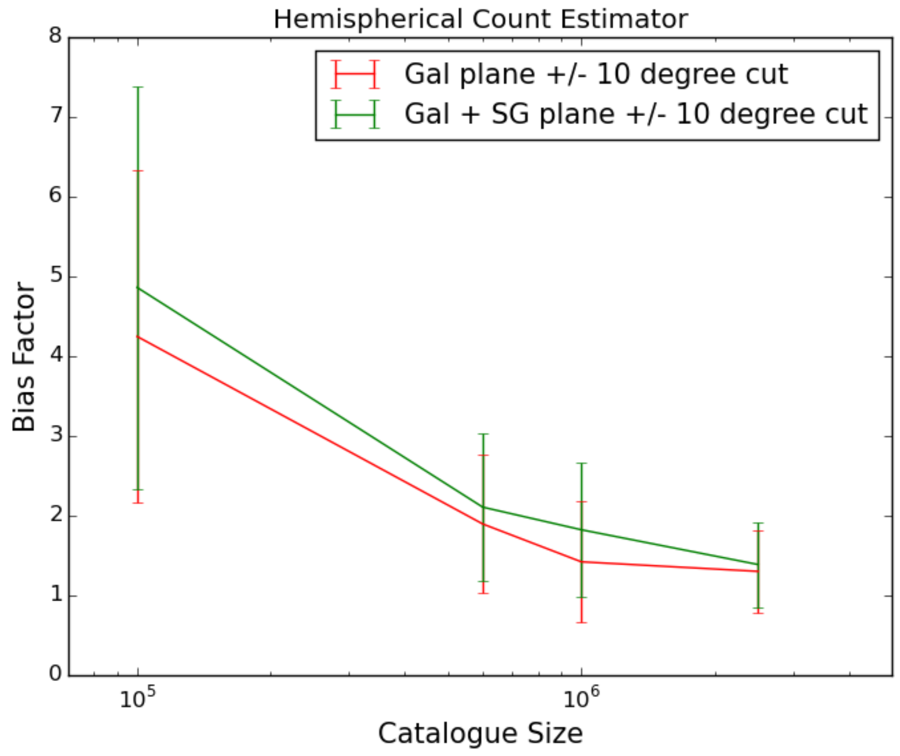

100 million ly
Capricornus Supercluster
Corona-Borealis Supercluster
Hercules Superclusters
Capricornus Void
Bootes Superclusters
Pavo-Indus Supercluster
180°
Bootes Void
Centaurus Supercluster
Shapley Supercluster
Sculptor Superclusters
Sculptor Void
270°
90°
Virgo
Coma Supercluster
Hydra
Ursa Major Supercluster
Pisces-Cetus Superclusters
Perseus-Pisces Supercluster
Leo Superclusters
0°
Horologium Supercluster
Columba Supercluster
Sextans Supercluster
r.powell

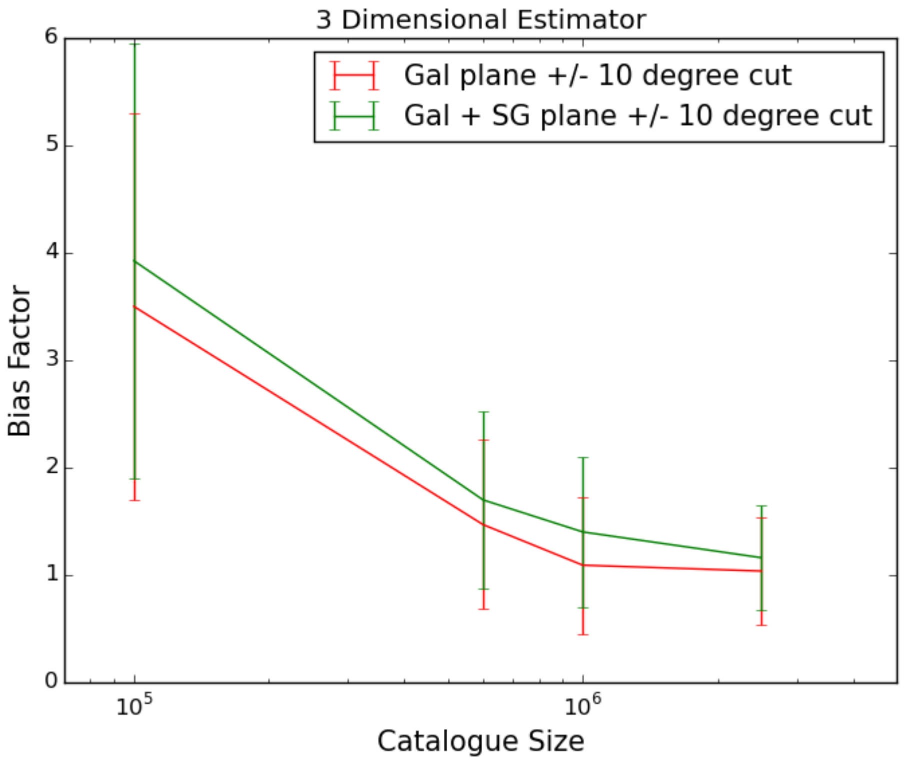

Measured V_b Amplitude
V_b for Standard ΛCDM Model
90% Allowed Deviation
Bulk Velocity (km/s)
R (Mpc/h)
0
200
400
600
800
1000
1200
0
50
100
150
COBE
PSCz
SBF
SFI
EN
SF
SNIa
PSCz
SMAC
EFAR
LP10
LP
PSCz
SCII

Estimators for the Dipole

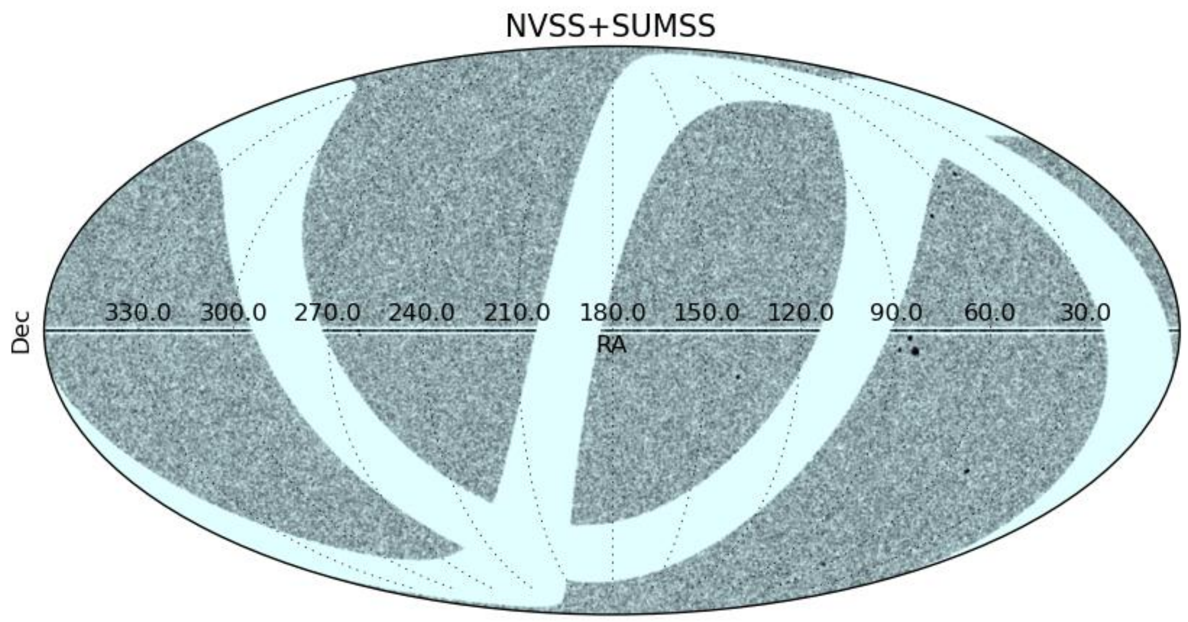
$$\vec{D}_H = \hat{z} * \frac{N_{UH} - N_{LH}}{N_{UH} + N_{LH}}$$

$$\vec{D}_{3D} = \frac{1}{N}\sum_{i=1}^{N} \hat{r}_i$$





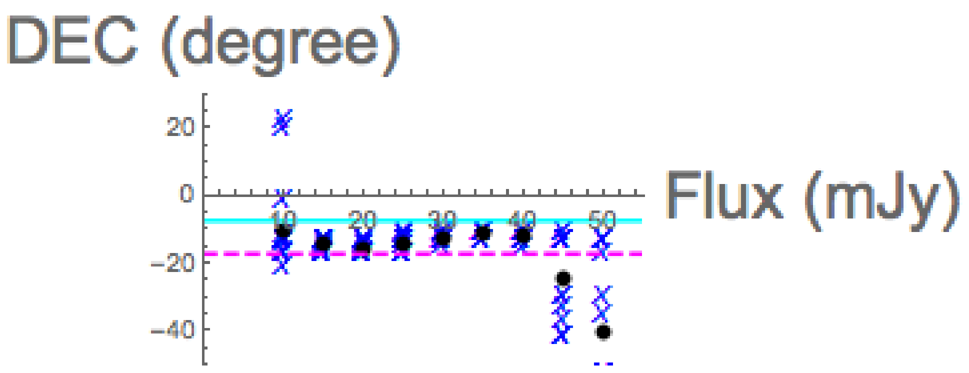
Local Sources contamination?

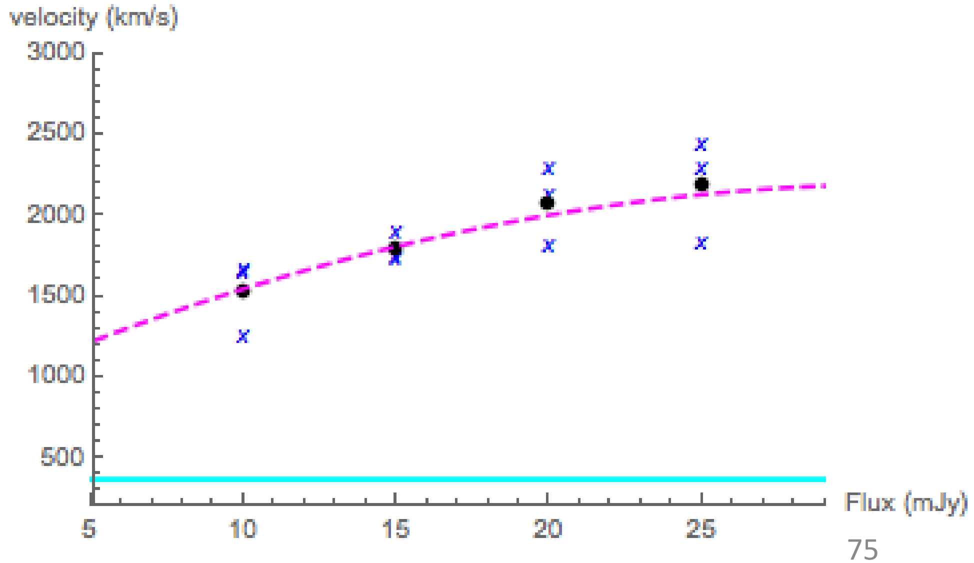


Remove the Supergalactic plane. Disk like structure containing the majority of clusters at z<0.03

Remove sources within 1 arcsecond of 2MRS z<0.03 sources

No significant impact on the velocity/direction of the dipole





	-2 log $\mathcal{L}_{\max}$	$q_{\rm m}$	$q_{\rm d}$	S	$j_0 - \Omega_k$	α	β	M_0	σ_{M_0}
Rubin & Hayden (22 param.) with no dipole	-331.6	-0.4574	–	–	0.1458	0.1345	3.067	-19.07	0.1074
As above with no acceleration ($q_{\rm m} = 0$)	-315.6	0	–	–	-1.351	0.1323	3.048	-19.01	0.1088
Rubin & Hayden (22 param.) with dipole $\propto e^{-z/S}$	-335.9	-0.3867	-0.2325	0.1825	-0.1779	0.1337	3.028	-19.06	0.1076
As above with no acceleration ($q_{\rm m} = 0$)	-326.9	0	-2.186	0.05034	-1.333	0.1325	3.02	-19.01	0.1087
Rubin & Hayden (16 param.) with no dipole	-242.4	-0.3873	–	–	0.2937	0.1345	3.063	-19.05	0.1080
As above with no acceleration ($q_{\rm m} = 0$)	-229.9	0	–	–	-0.8444	0.1325	3.051	-19.00	0.1094
Rubin & Hayden (16 param.) with dipole $\propto e^{-z/S}$	-250.2	-0.3329	-0.2091	0.2726	0.04258	0.1336	3.021	-19.04	0.1081
As above with no acceleration ($q_{\rm m} = 0$)	-241.2	0	-0.3585	0.1794	-0.8645	0.132	3.009	-19.00	0.1093
Rubin & Hayden (16 + 3 param.) with no dipole	-253.4	-0.09894	–	–	-0.102	0.1346	3.023	-19.07, -19.00, -18.94, -18.78	0.1082
As above with no acceleration ($q_{\rm m} = 0$)	-253	0	–	–	-0.2661	0.1344	3.016	-19.06, -18.99, -18.92, -18.77	0.1084

Even with the sample and redshift dependent treatment for $x_{1,0}$ and c_0 proposed by R&H,q_m=0 is disfavoured only at 2.4 sigma and allows for a large q_d extending to z~0.18

If $x_{1,0}$ and c_0 can be sample or redshift dependent, why not M_0? Undermines the use of SN1a as standard candles but justified by AIC.

Planck 2015

Parameter	*Planck* TT+lowP+lensing
$\Omega_b h^2$	0.02226 ± 0.00023
$\Omega_c h^2$	0.1186 ± 0.0020
$100\theta_{MC}$	1.04103 ± 0.00046
τ	0.066 ± 0.016
$\ln(10^{10} A_s)$	3.062 ± 0.029
n_s	0.9677 ± 0.0060
H_0	67.8 ± 0.9
Ω_m	0.308 ± 0.012
$\Omega_m h^2$	0.1415 ± 0.0019
$\Omega_m h^3$	0.09591 ± 0.00045
σ_8	0.815 ± 0.009
$\sigma_8 \Omega_m^{0.5}$	0.4521 ± 0.0088
Age/Gyr	13.799 ± 0.038
r_{drag}	147.60 ± 0.43
k_{eq}	0.01027 ± 0.00014

https://arxiv.org/pdf/1706.09309.pdf

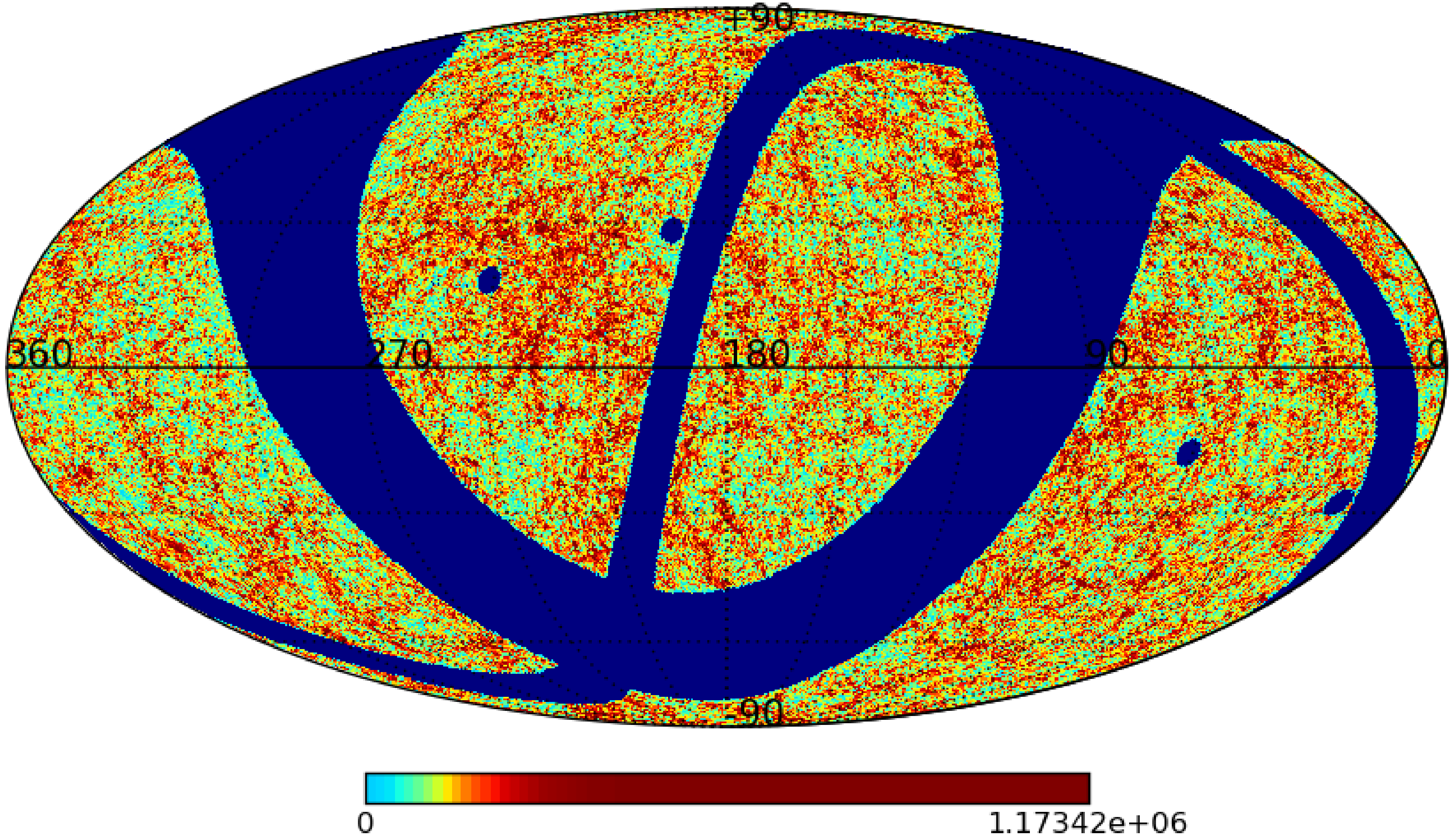
https://arxiv.org/pdf/1505.07800.pdf

On the measurement of cosmological parameters

Rupert A. C. Croft, Matthew Dailey (CMU)

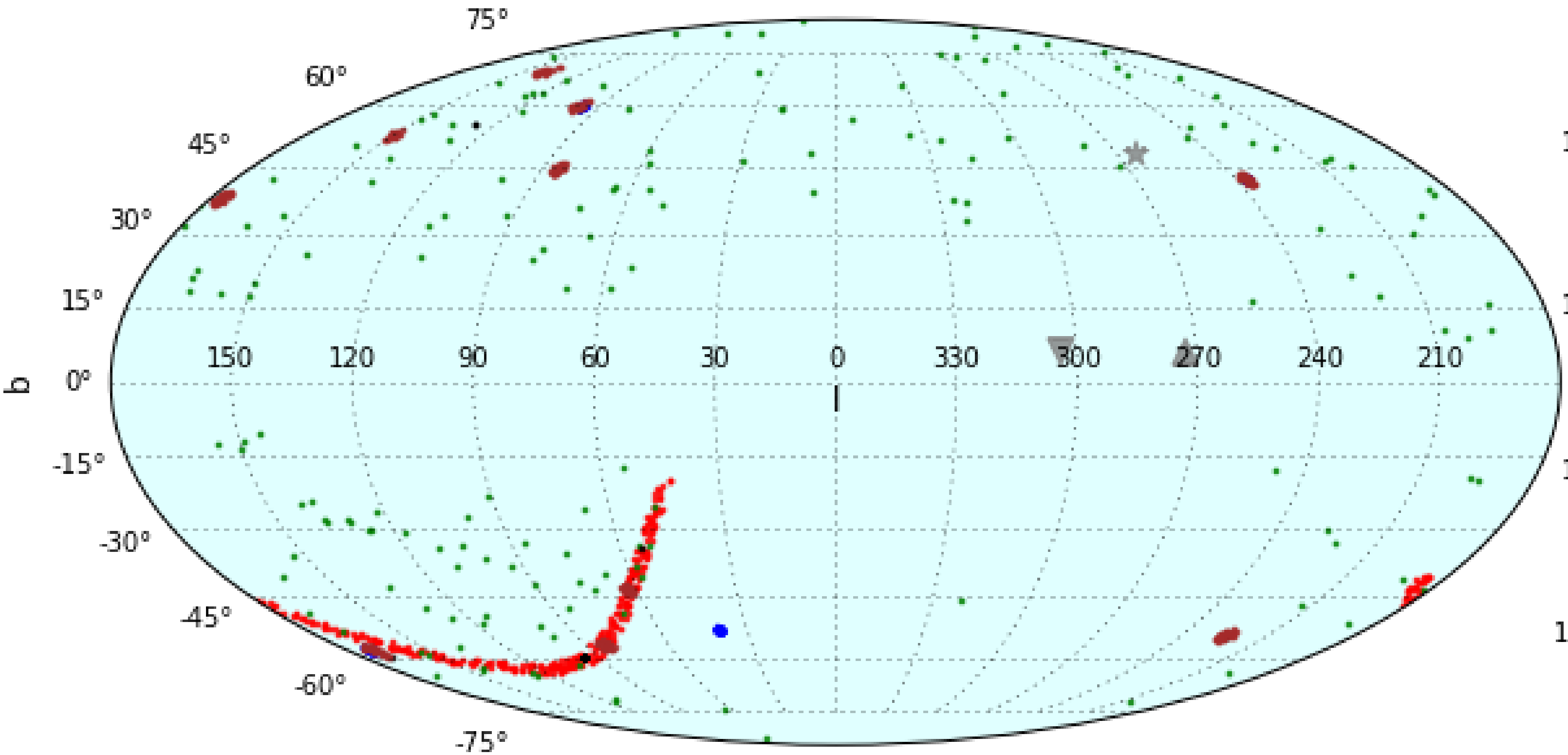
(Submitted on 14 Dec 2011 (v1), last revised 21 Jul 2015 (this version, v2))

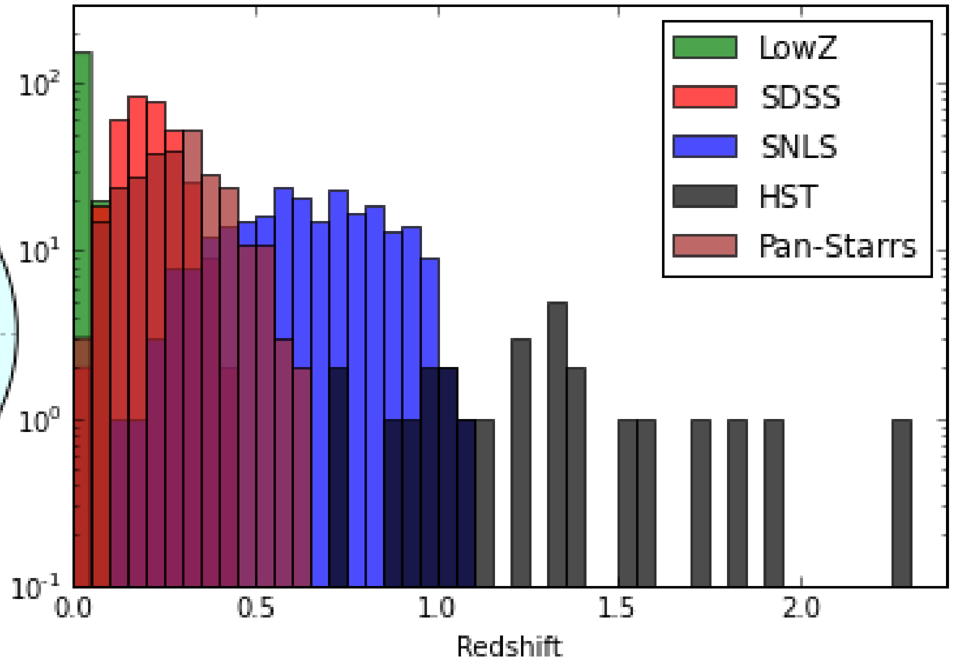
We have catalogued and analysed cosmological parameter determinations and their error bars published between the years 1990 and 2010. Our study focuses on the number of measurements, their precision and their accuracy. The accuracy of past measurements is gauged by comparison with the WMAP7 results. The 637 measurements in our study are of 12 different parameters and we place the techniques used to carry them out into 12 different categories. We find that the number of published measurements per year in all 12 cases except for the dark energy equation of state parameter w_0 peaked between 1995 and 2004. Of the individual techniques, only BAO measurements were still rising in popularity at the end of the studied time period. The fractional error associated with most measurements has been declining relatively slowly, with several parameters, such as the amplitude of mass flucttutations sigma_8 and the Hubble constant H_0 remaining close to the 10% precision level for a 10-15 year period. The accuracy of recent parameter measurements is generally what would be expected given the quoted error bars, although before the year 2000, the accuracy was significantly worse, consistent with an average underestimate of the error bars by a factor of ~2. When used as complement to traditional forecasting techniques, our results suggest that future measurements of parameters such as fNL, and w_a will have been informed by the gradual improvment in understanding and treatment of systematic errors and are likely to be accurate. However, care must be taken to avoid the effects of confirmation bias, which may be affecting recent measurements of dark energy parameters. For example, of the 28 measurements of Omega_Lambda in our sample published since 2003, only 2 are more than 1 sigma from the WMAP results. Wider use of blind analyses in cosmology could help to avoid this.


+90
360
270
180
90
0
-90
0
1.17342e+06

The Pantheon compilation

Scolnic et al. Astrophys.J. 859 (2018) no.2, 101

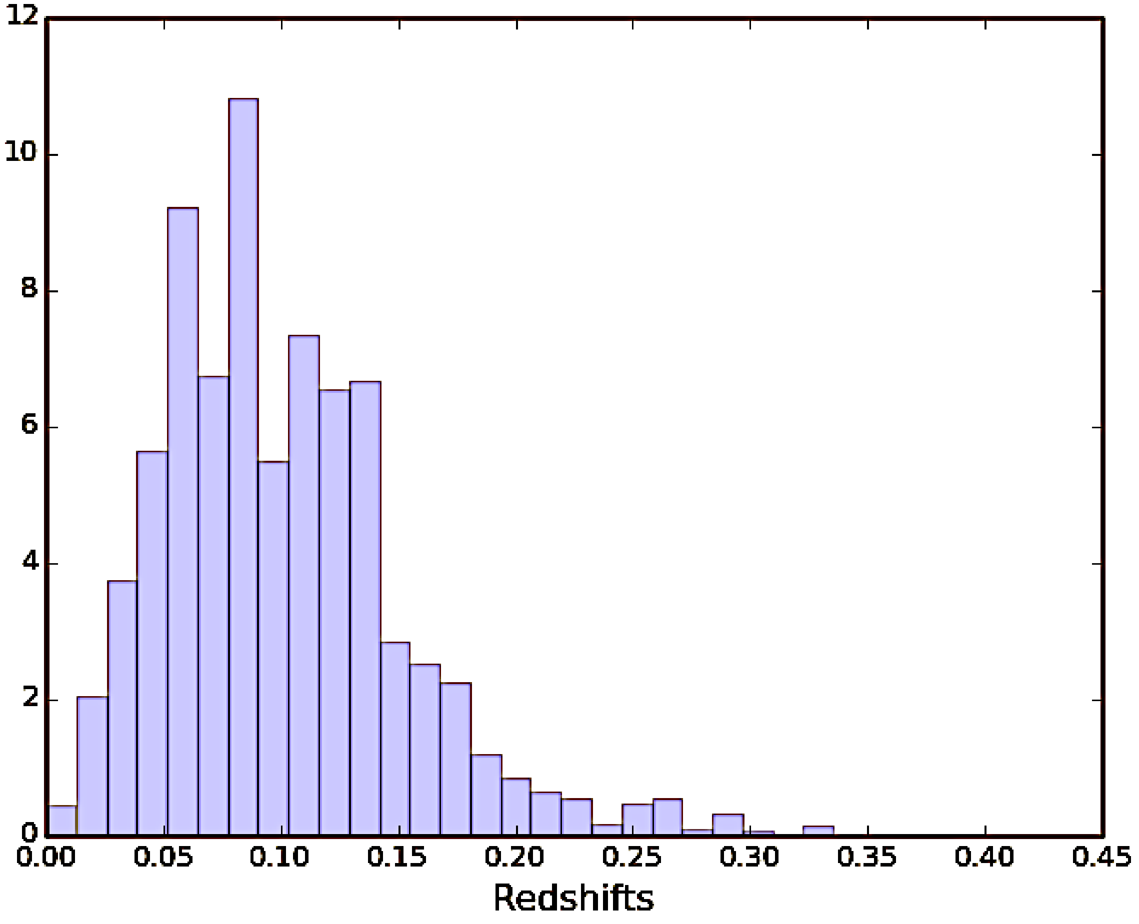




JLA + additional SN1a from Pan Starrs and HST
1048 SN1a, redshifts corrected for peculiar velocities using the 2M++ flow field
890 are in the hemisphere opposite the 2M++ bulk flow

However, we use only JLA!

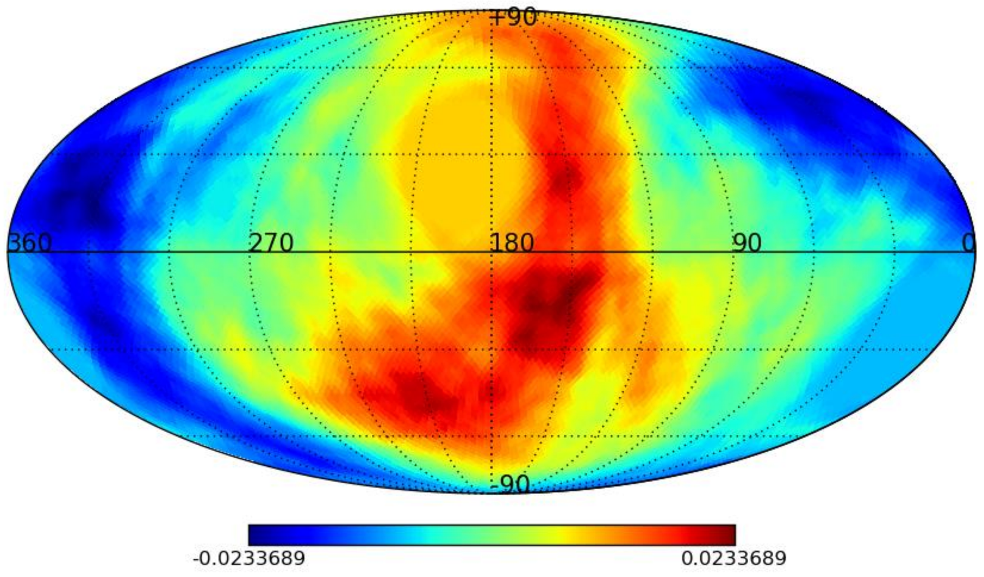
Redshift distribution of the removed sources

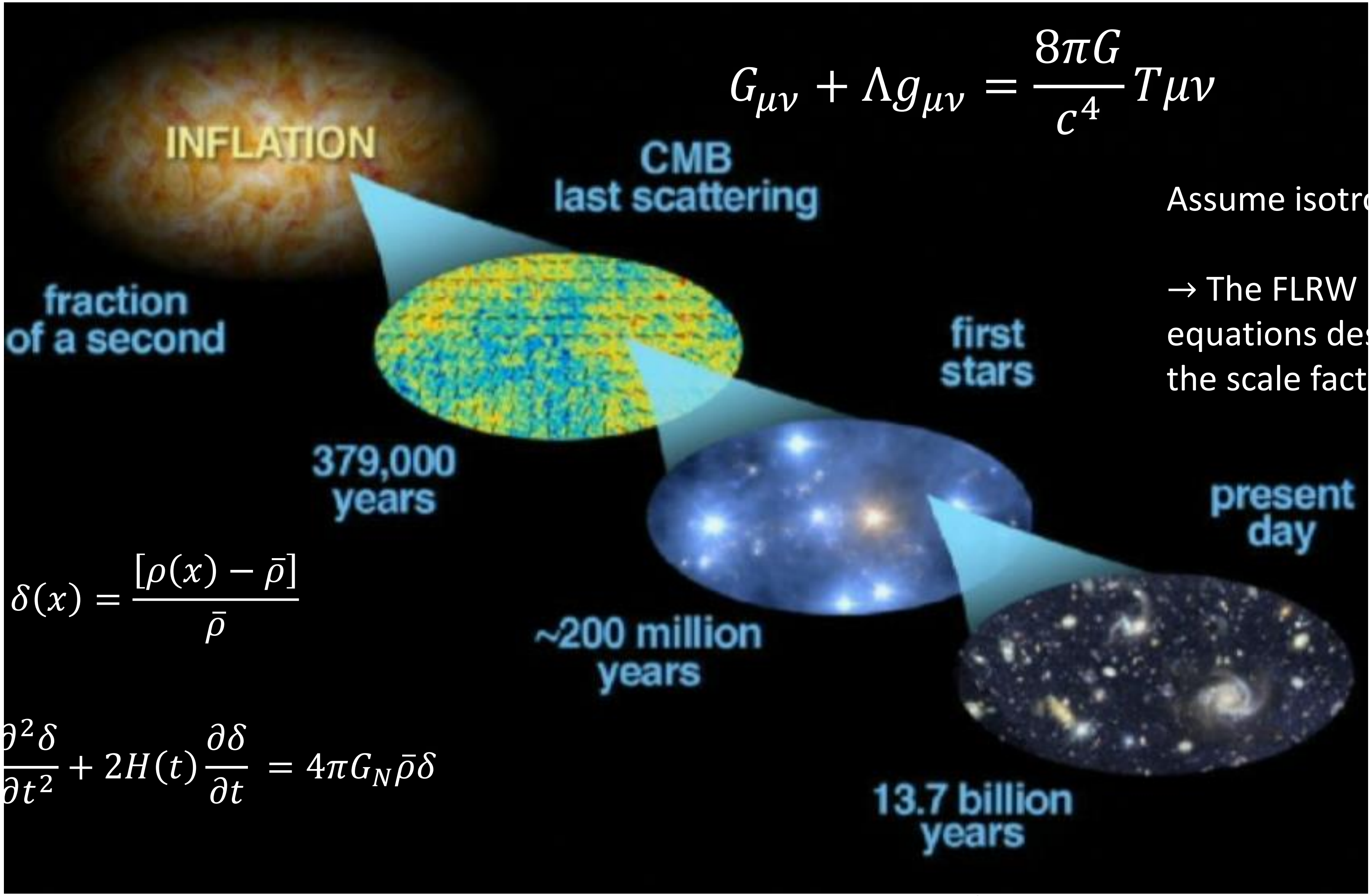


By cross correlating with Galaxy and Mass Assembly

d = 0.0124 >1200 km/s if fully kinematic
172.6° RA, -6.6° Dec (~4.5° from CMB)

Total dipole is at least 4.2σ statistically significant.





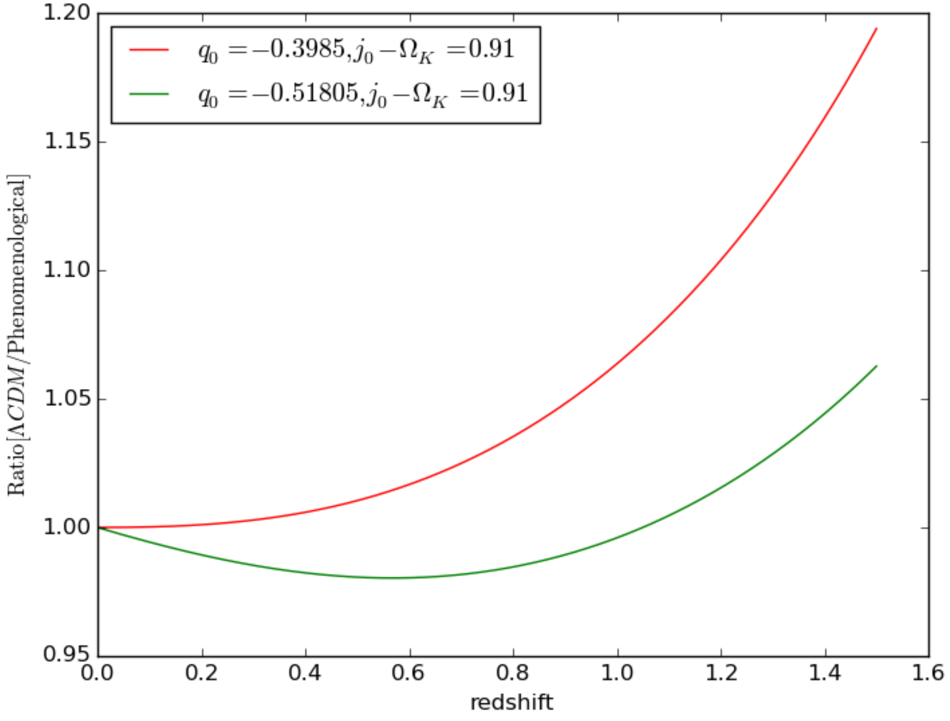
$$G_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T\mu\nu$$

Assume isotr

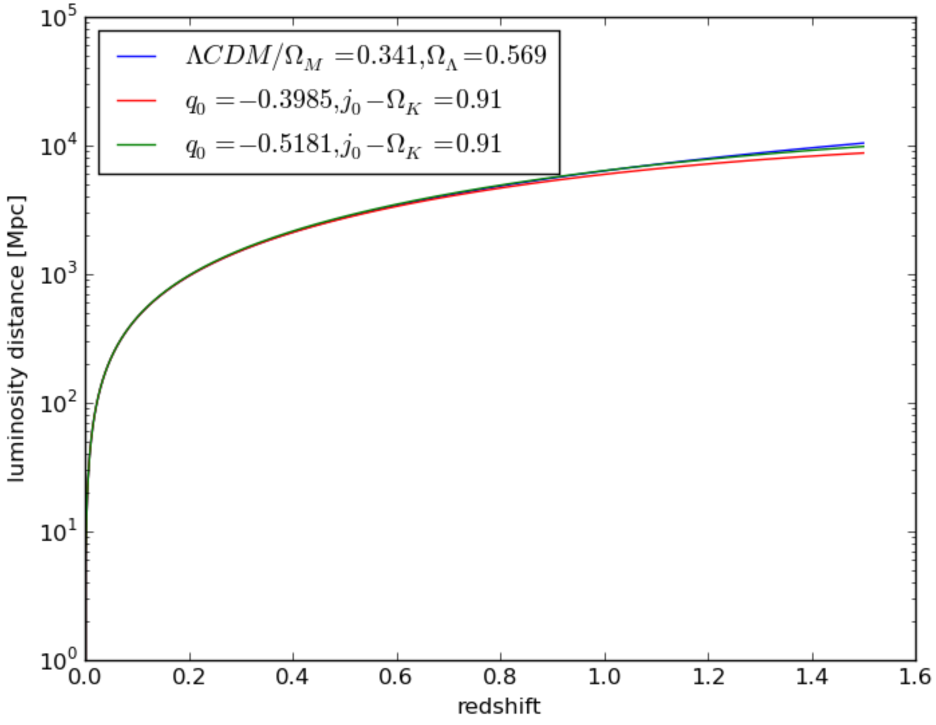
→ The FLRW
equations des
the scale fact

$$\delta(x) = \frac{[\rho(x) - \bar{\rho}]}{\bar{\rho}}$$

$$\frac{\partial^2\delta}{\partial t^2} + 2H(t)\frac{\partial\delta}{\partial t} = 4\pi G_N \bar{\rho}\delta$$



1.20
1.15
1.10
1.05
1.00
0.95
0.0 0.2 0.4 0.6 0.8 1.0 1.2 1.4 1.6
redshift
Ratio[ΛCDM/Phenomenological]
$q_0 = -0.3985, j_0 - \Omega_K = 0.91$
$q_0 = -0.51805, j_0 - \Omega_K = 0.91$



10^5
10^4
10^3
10^2
10^1
10^0
0.0 0.2 0.4 0.6 0.8 1.0 1.2 1.4 1.6
redshift
luminosity distance [Mpc]
$\Lambda CDM/\Omega_M = 0.341, \Omega_\Lambda = 0.569$
$q_0 = -0.3985, j_0 - \Omega_K = 0.91$
$q_0 = -0.5181, j_0 - \Omega_K = 0.91$

Residual clustering dipole

- For a Copernican observer:
- $\langle D_{cls} \rangle = \sqrt{\frac{9}{4\pi} C_1}$
- $C_l = b^2 \frac{2}{\pi} \int_0^\infty f_l(k)^2 P(k) k^2 dk$
- $f_l(k) = \int_0^\infty j_l(kr) f(r) dr$
- $f(r) = \frac{H(z)}{H_0 r_0} \frac{dN}{dz}$

Using Planck 2015 cosmological parameters and astropy, using the the redshift distribution as dN/dz

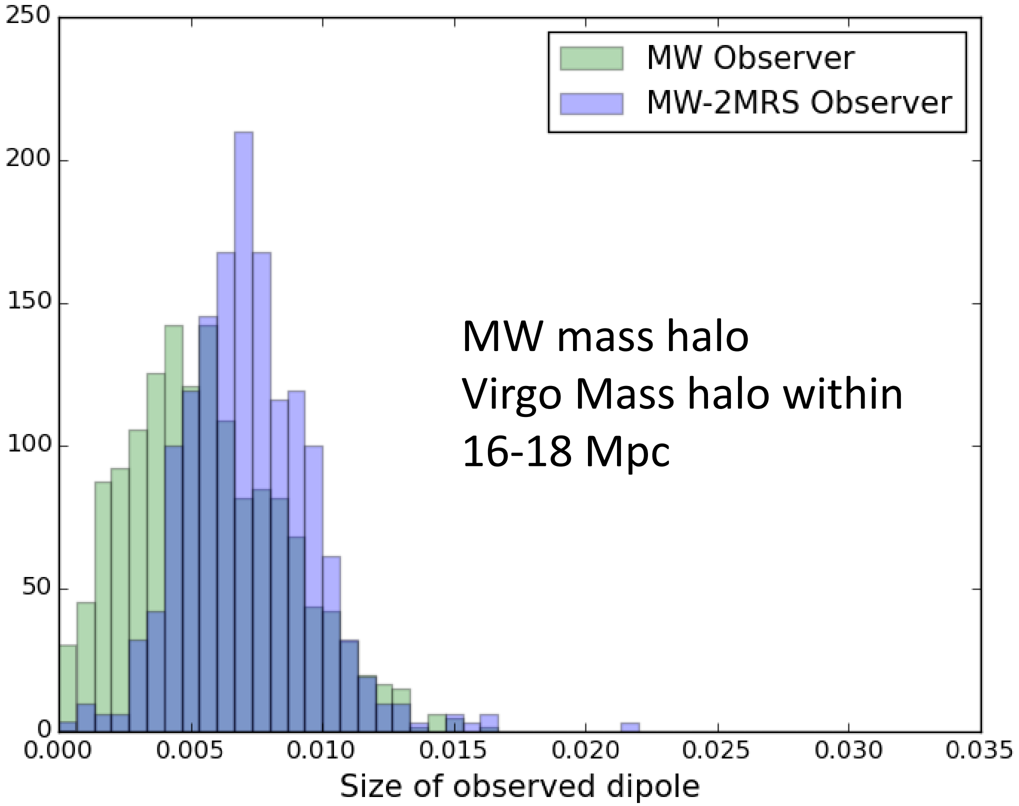
$\langle D_{cls} \rangle$ < 0.0018
In the final sample

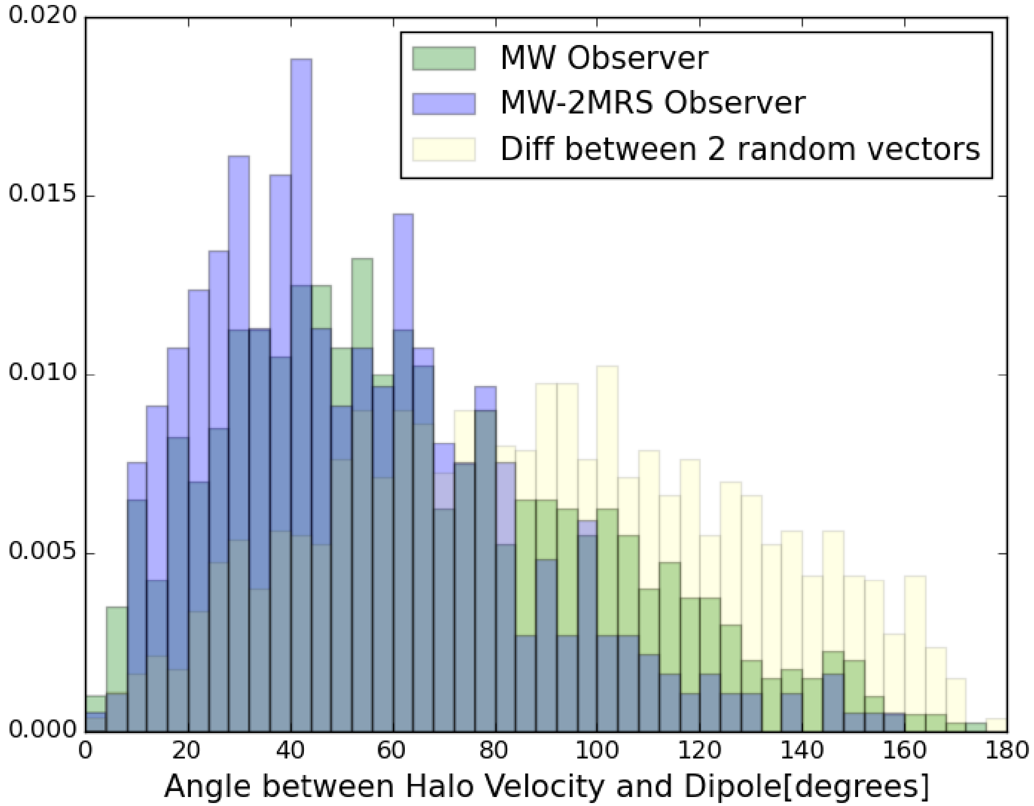
$D_{kin} = 0.0106$

Velocity of ~3000 km/s

Dark Sky N Body Simulations

First trillion particle simulation of the ΛCDM universe.





Only ~<1% of halos with MW-like mass and velocity are inside bulk flows > 240 km/s on scales exceeding 260 Mpcs

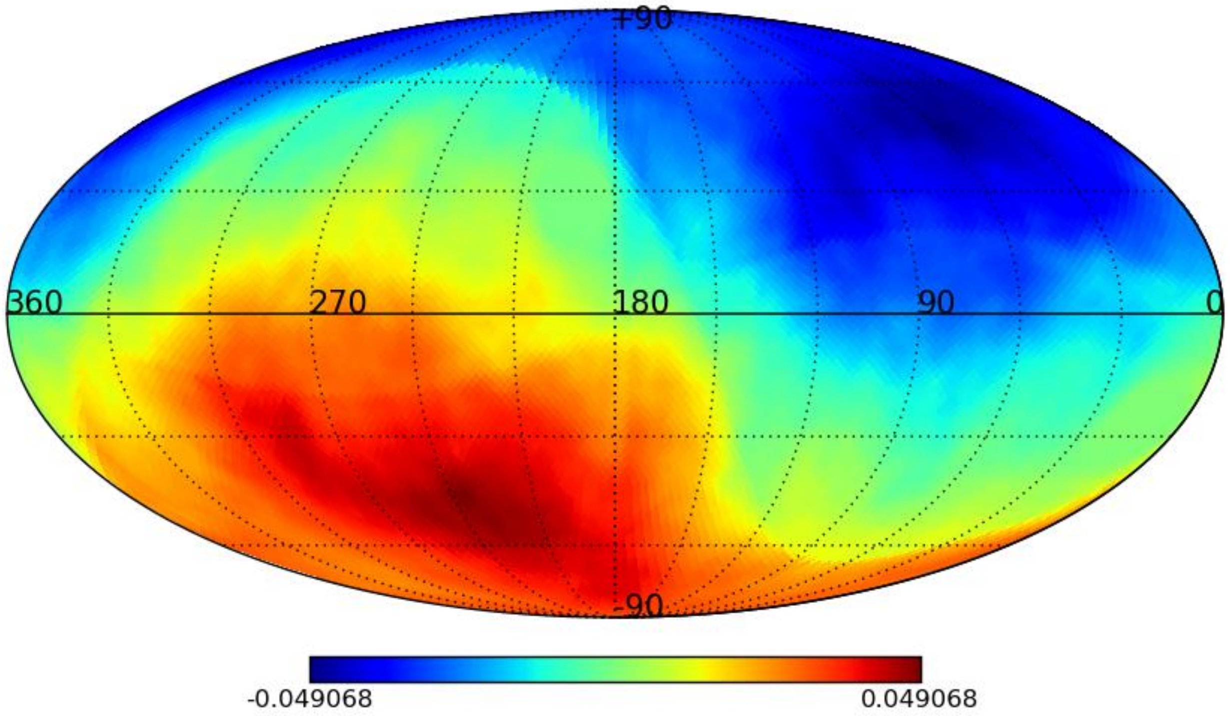
$\langle D_{cls} \rangle$ = 0.0076 +/- 0.0022

$\langle D_{kin} \rangle$ = 0.0048 +/- 0.0024

Getting rid of the stars

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

How approximate? Cosmological Backreaction

Is there proof that backreaction of inhomogeneities is irrelevant in cosmology?

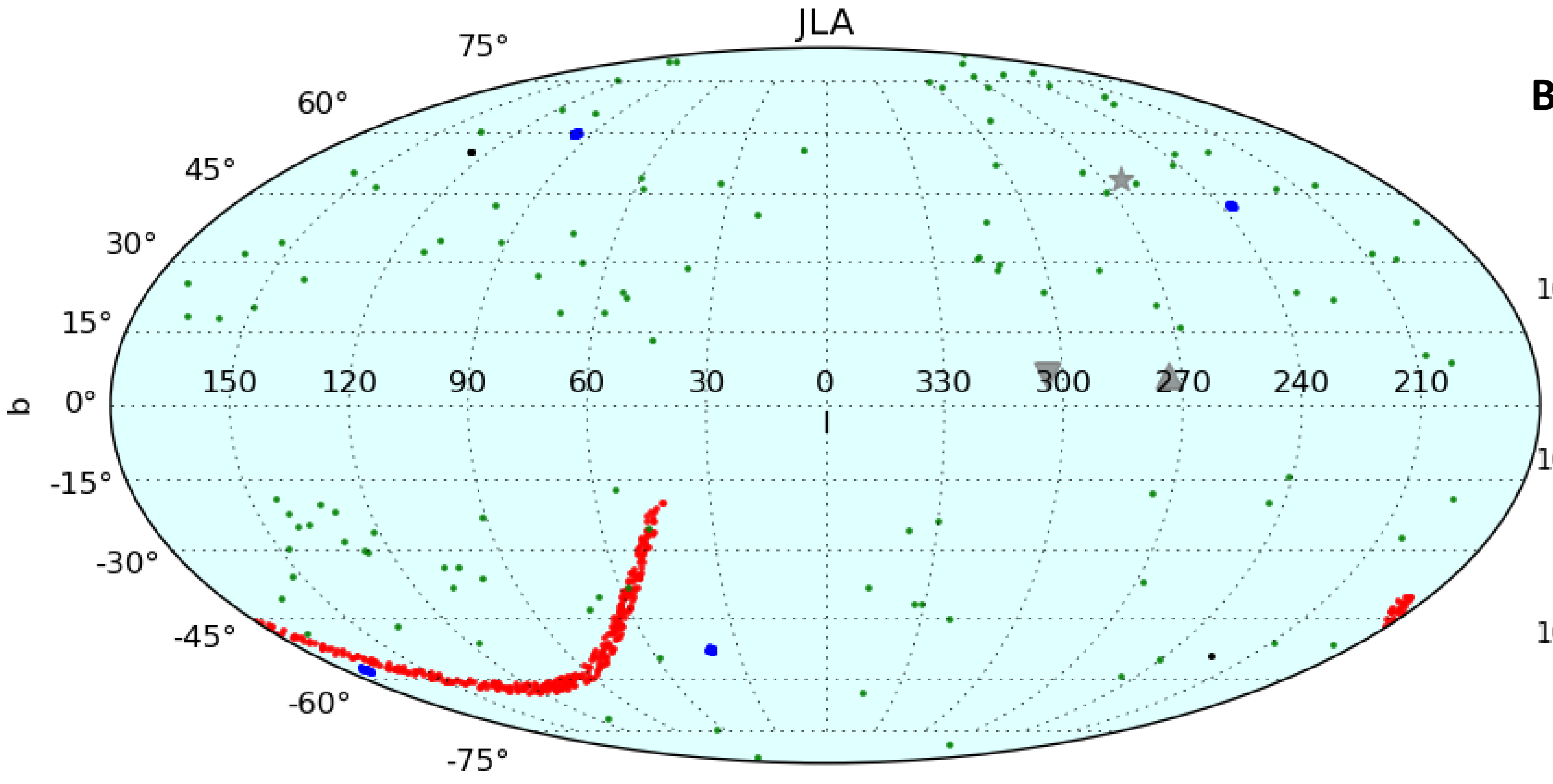
T Buchert[1], M Carfora[2], G F R Ellis[3], E W Kolb[4], M A H MacCallum[5], J J Ostrowski[6,1,†], S Räsänen[7], B F Roukema[6,1,†], L Andersson[8], A A Coley[9], and D L Wiltshire[10]

[1]Université de Lyon, Observatoire de Lyon, Centre de Recherche Astrophysique de Lyon, CNRS UMR 5574: Université Lyon 1 and École Normale Supérieure de Lyon, 9 avenue Charles André, F–69230 Saint–Genis–Laval, France
[2]Dipartimento di Fisica, Università degli Studi di Pavia, via A. Bassi 6, I–27100 Pavia, Italy, and Istituto Nazionale di Fisica Nucleare, Sezione di Pavia, via A. Bassi

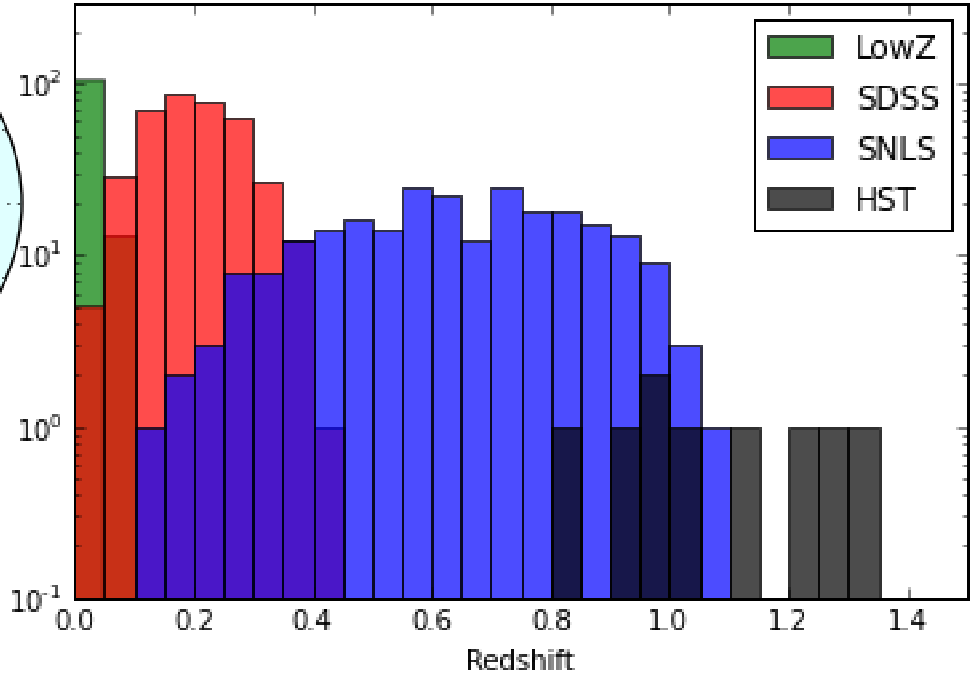
Exact but closer to reality than FLRW -> Swiss Cheese Universes.

- Underdensities always expand a little faster than overdensities.
- They come to dominate the volume
- Thus any inhomogeneity should lead to faster expansion.
- Marra, Kolb, Matarrese 2007 , Rasanen 2012, Rasanen 2015
- Can explain most of of observed dark energy
- Backreaction even within perturbative gravity : Adamek, Class. Quantum Grav. 36, 014001 (2019)

2014 : The Joint Lightcurve Analysis (JLA) Sample



Betoule et. al. Astron.Astrophys. 568 (2014) A22



The SDSSII/SNLSIII Joint Lightcurve Analysis (JLA) catalogue of SN1a
740 SN1a , 551 of which are in the hemisphere opp to the CMB motion
Redshifts corrected using SMAC, which has a bulk flow (gray triangle)
631 are in the opp hemisphere to SMAC BF

SNe down to z= 0.01 reintroduced
CMB frame observables:

Spectral Adaptive Lightcurve Template

(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

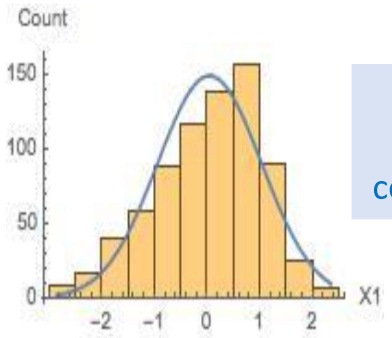
There may well be other variables that the magnitude correlates with …

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

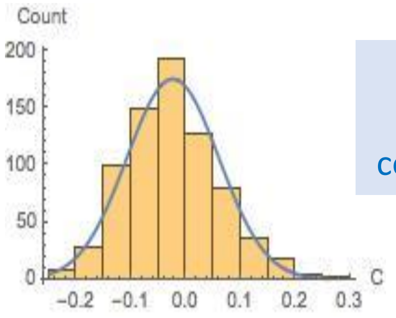
$$\mathcal{L} = \text{probability density}(\text{data}|\text{model})$$

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

Well-approximated as Gaussian



JLA data
'Stretch'
corrections



JLA data
'Colour'
corrections

$$p[(M, x_1, c)|\theta] = p(M|\theta)p(x_1|\theta)p(c|\theta),$$
$$p(M|\theta) = \frac{1}{\sqrt{2\pi\sigma_M^2}} \exp\left(-\left[\frac{M - M_0}{\sigma_{M0}}\right]^2 / 2\right)$$
$$p(x_1|\theta) = \frac{1}{\sqrt{2\pi\sigma_{x0}^2}} \exp\left(-\left[\frac{x_1 - x_{10}}{\sigma_{x0}}\right]^2 / 2\right)$$
$$p(c|\theta) = \frac{1}{\sqrt{2\pi\sigma_{c0}^2}} \exp\left(-\left[\frac{c - c_0}{\sigma_{c0}}\right]^2 / 2\right)$$

Likelihood

$$p(Y|\theta) = \frac{1}{\sqrt{|2\pi\Sigma_l|}} \exp\left[-\frac{1}{2}(Y - Y_0)\Sigma_l^{-1}(Y - Y_0)^{\mathrm{T}}\right]$$

$$p(\hat{X}|X,\theta) = \frac{1}{\sqrt{|2\pi\Sigma_d|}} \exp\left[-\frac{1}{2}(\hat{X} - X)\Sigma_d^{-1}(\hat{X} - X)^{\mathrm{T}}\right]$$

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

intrinsic distributions

cosmology

SALT2

Confidence regions

$$p_{\mathrm{cov}} = \int_0^{-2\log\mathcal{L}/\mathcal{L}_{\max}} \chi^2(x;\nu)dx$$

$$\mathcal{L}_p(\theta) = \max_{\phi} \mathcal{L}(\theta, \phi)$$

1,2,3-sigma

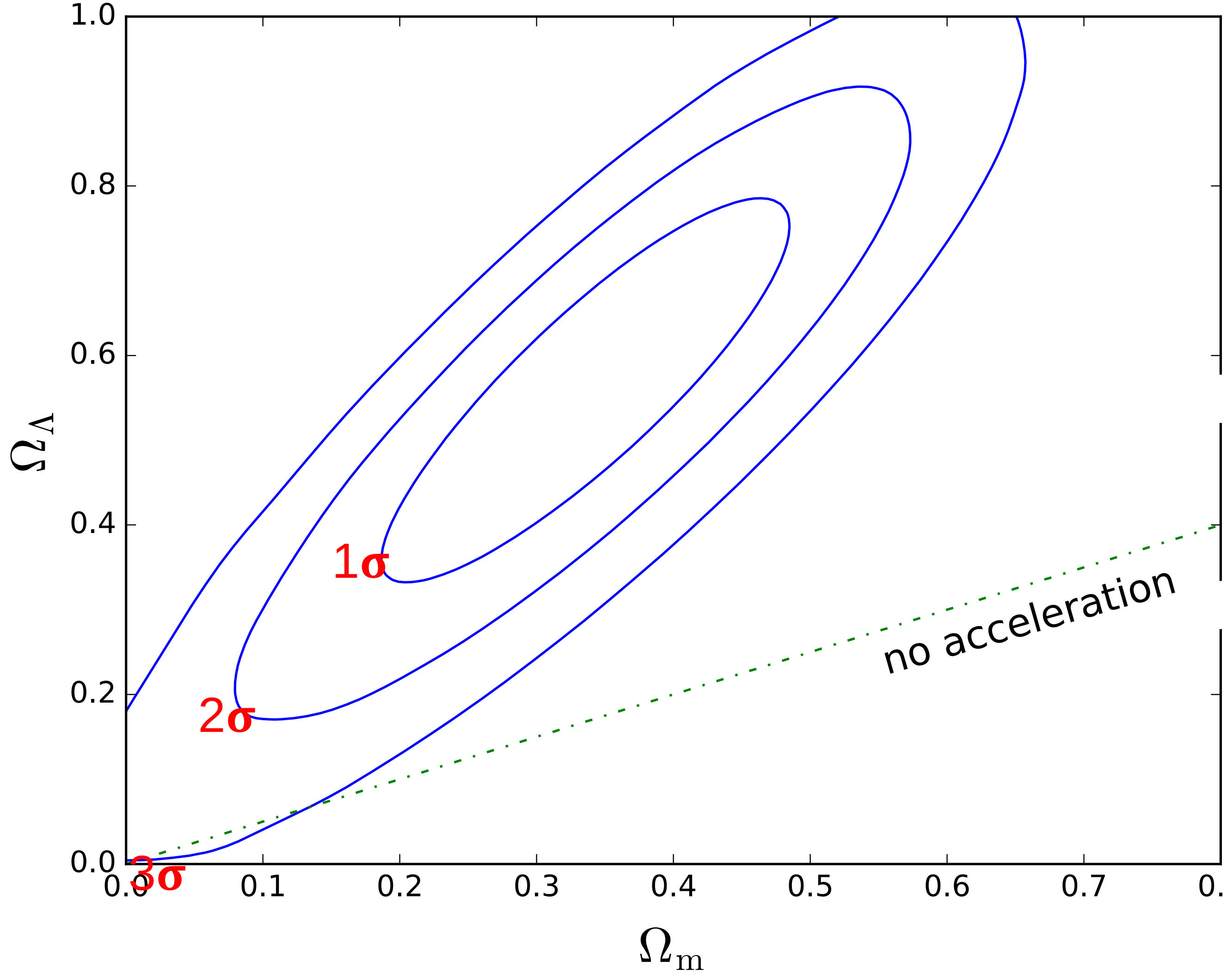
solve for Likelihood value

Simultaneously fit for

Ω_{M}
Ω_Λ
q_d
S
α
$x_{1,0}$
$\sigma_{x_{1,0}}$
β
c_0
σ_{c_0}
M_0
σ_{M_0}

Data consistent with uniform expansion @<3σ!

profile likelihood



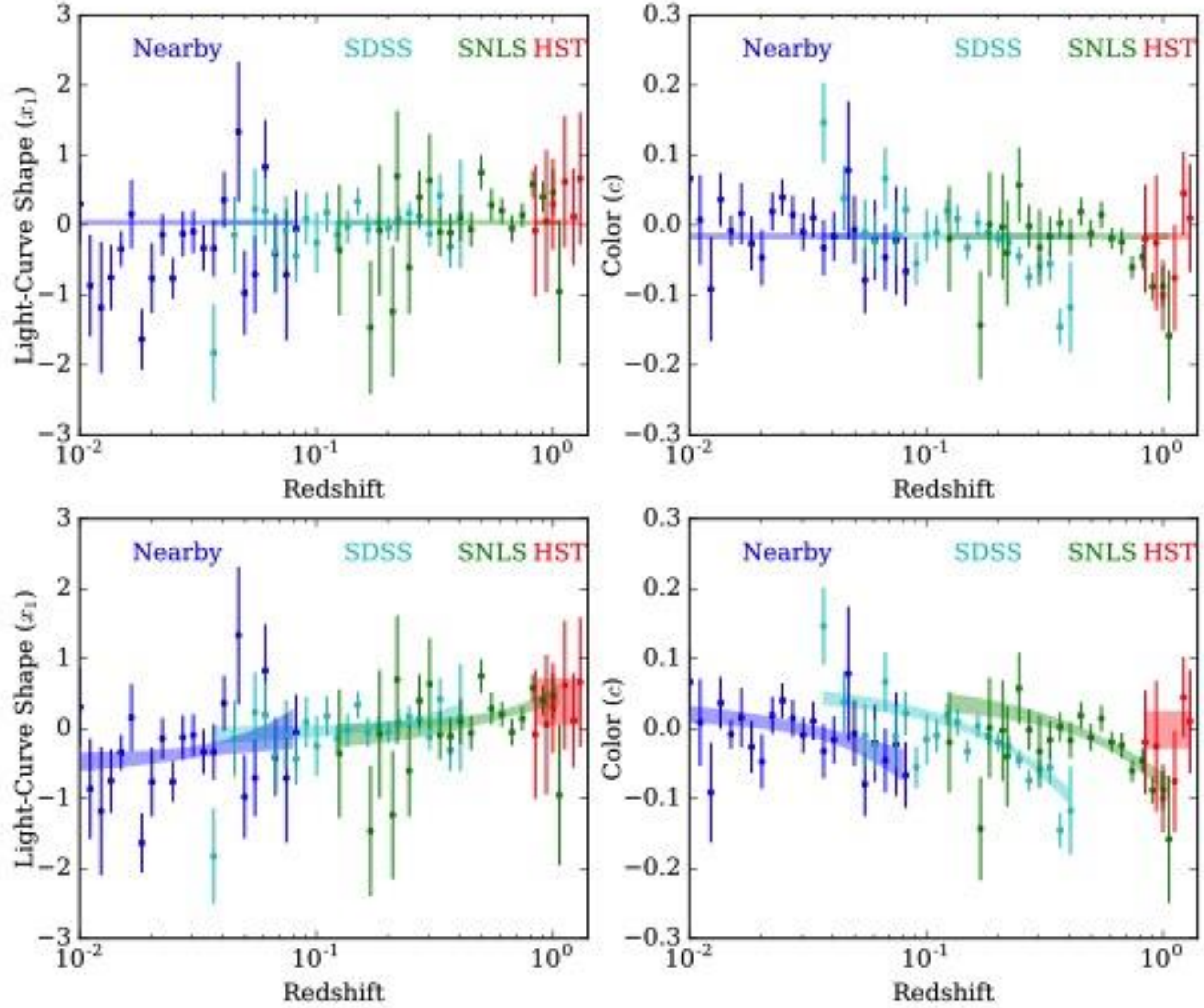
<u>MLE, *best fit*</u>

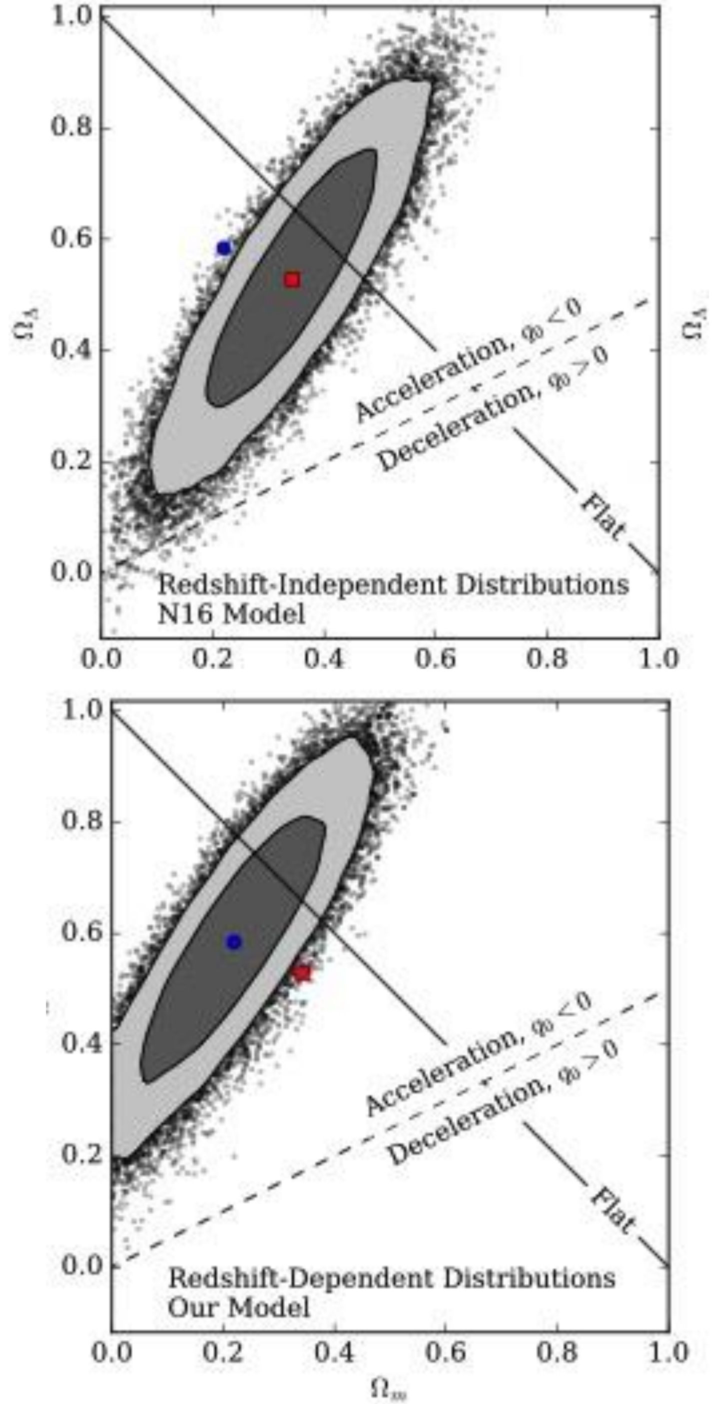
Ω_M	0.341
Ω_Λ	0.569
α	0.134
x_0	0.038
σ^2_{x0}	0.931
β	3.058
c_0	-0.016
σ^2_{c0}	0.071
M_0	-19.05
σ^2_{M0}	0.108

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

Rubin & Hayden 2016
Added 12 parameters to this 10 parameter fit, to claim significance > 4sigma

Rubin & Hayden 2016





Peculiar velocity impact on SN1a magnitude

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

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

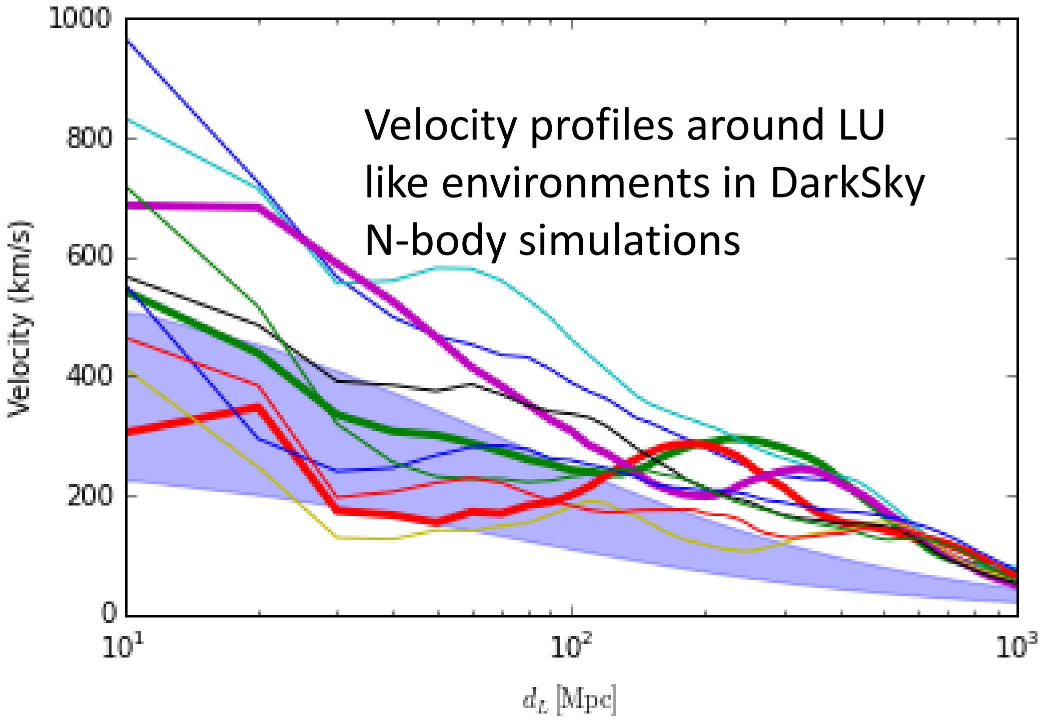
Davis et. al. Astrophys.J. 741 (2011) 67

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

```
#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
```

$z_{hel} \rightarrow measured$

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



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).

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

Luminosity distance in the FLRW Universe

Exact

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

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

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

Kinematic

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

Matt Visser 2004

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

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

What we mean by tilt : $q_0 \rightarrow q_m + q_d \cos\left(\theta_{|cmb-SN|}\right) e^{-z/S}$

A study of Dipolar Signal in distant Quasars with various observables

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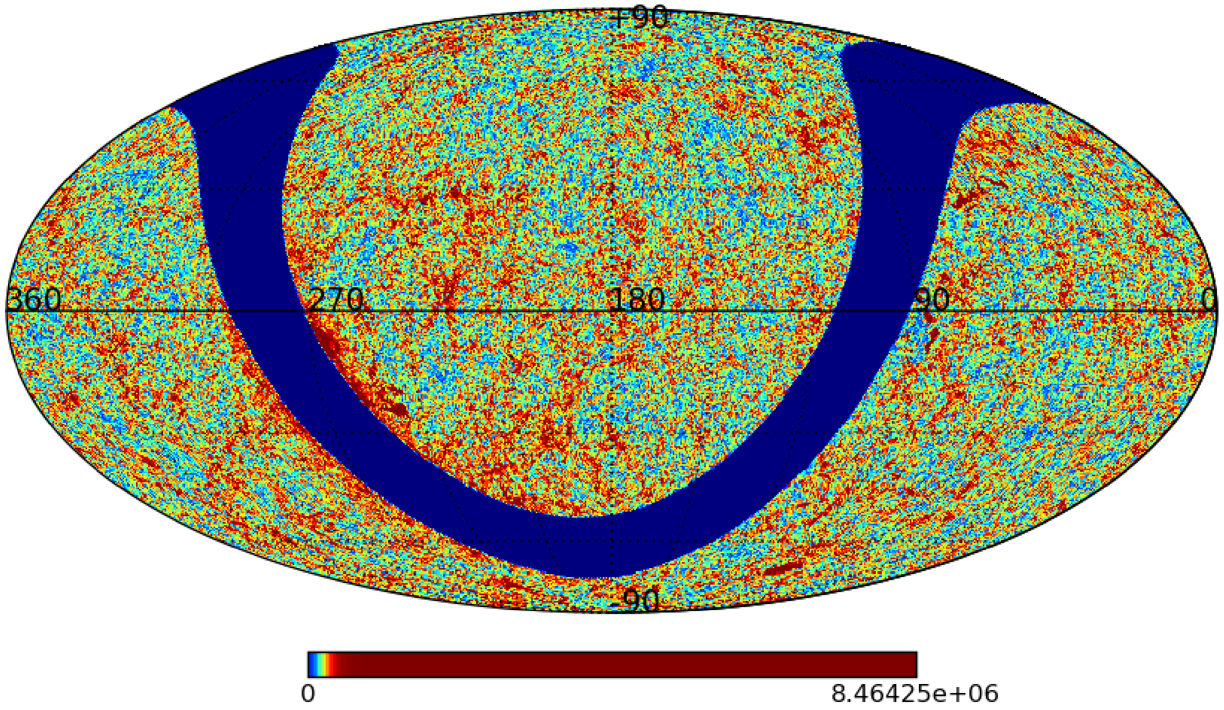
Abstract. We study the signal of anisotropy in AGNs/quasars of CatWISE2020 catalogue using different observables. It has been reported earlier that this data shows a strong signal of dipole anisotropy in the source number counts. We test this claim using two independent data analysis procedures and find our number count dipole consistent with the earlier results. In addition to number counts, we test for the anisotropy signal in two other observables — mean spectral index $\bar{\alpha}$ and mean flux density $\bar{B}$. We find a dipole signal of considerable strength both in the mean spectral index and the mean flux density. The dipole in mean flux density points towards the galactic center and becomes very weak after imposing a flux cut to remove sources with flux greater than 1 mJy. This can be attributed to the presence of some bright sources. The signal in mean spectral index, however, is relatively stable as a function of both flux and galactic cuts. The dipole in this observable points roughly opposite to the galactic center and hence most likely arises due to galactic bias. Hence, the signal in both the mean spectral index and mean flux density appears to be consistent with isotropy.

AllWISE-Galaxies

Star galaxy separation 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

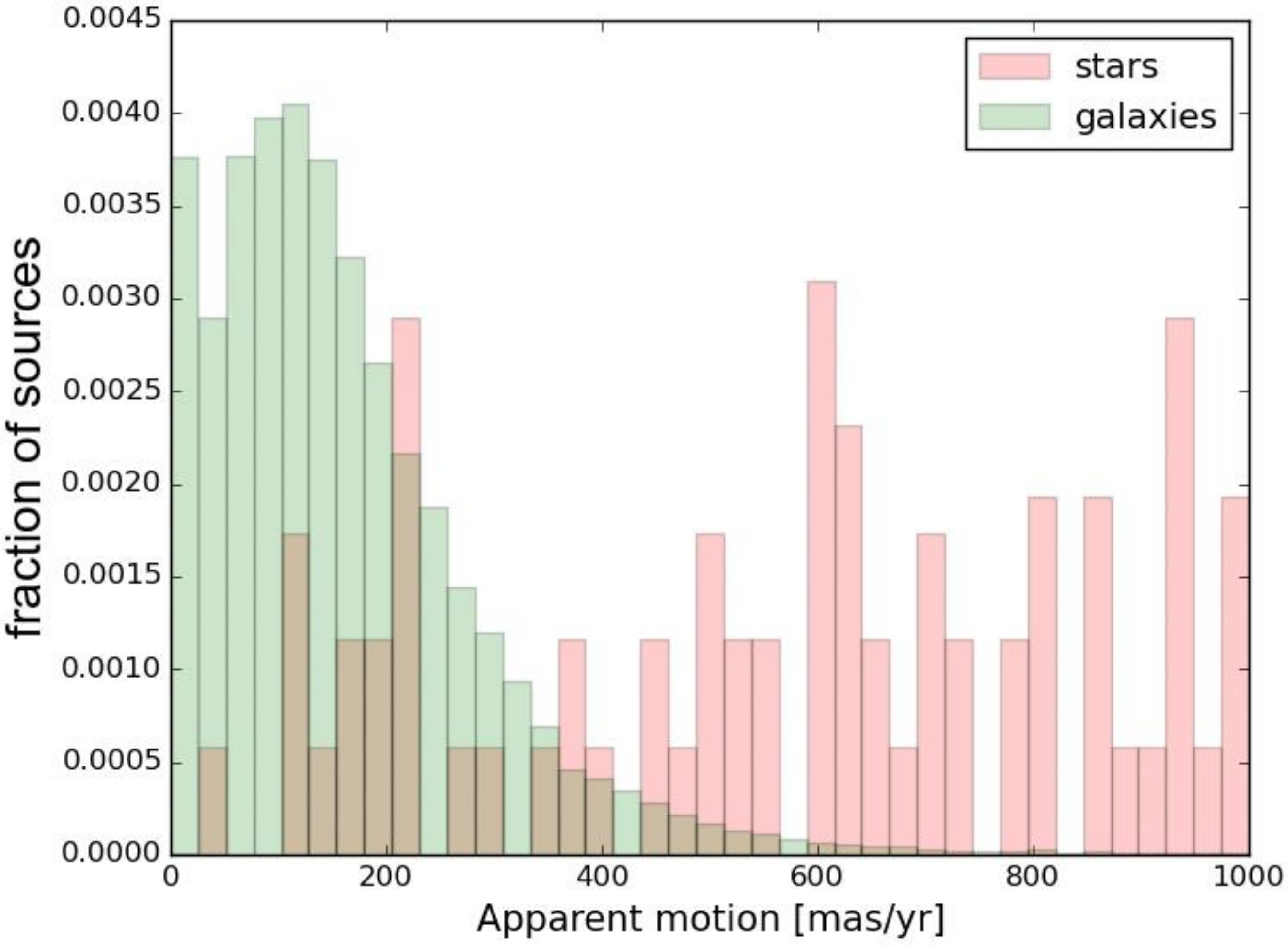
110 degrees from the CMB direction

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

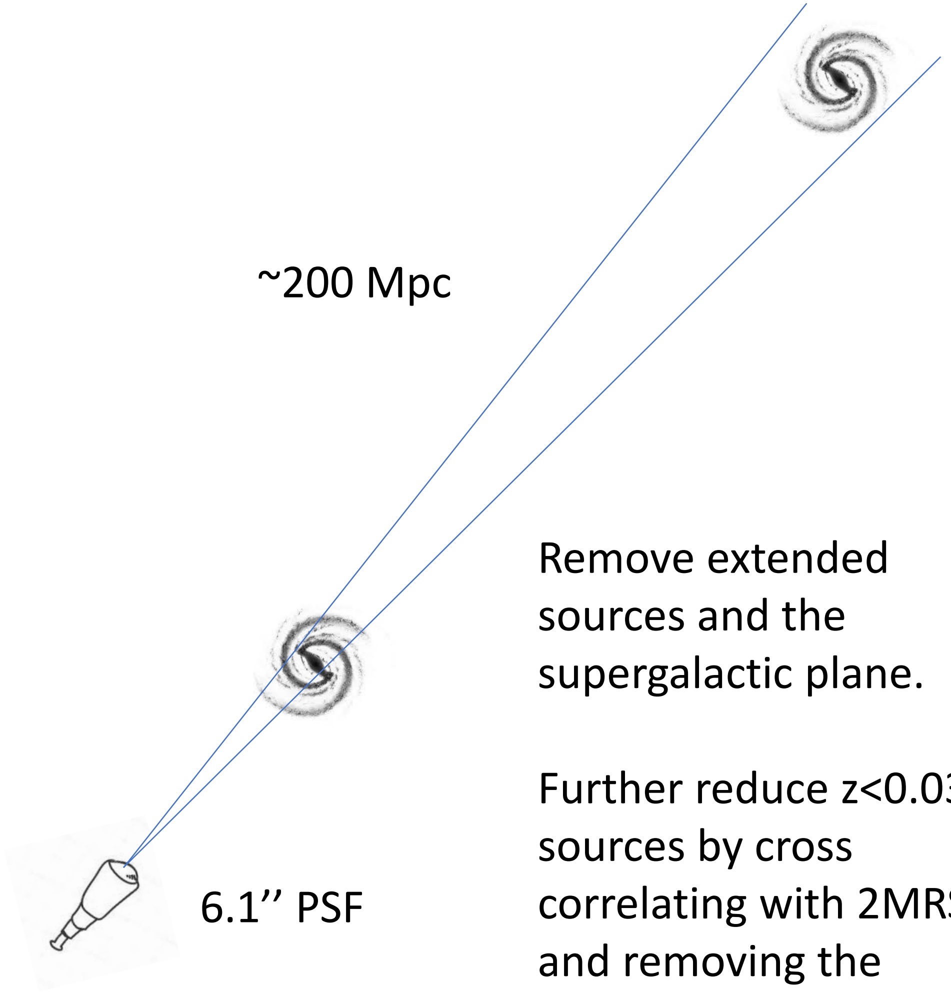
Cuts on apparent motion can bring star contamination down to 0.1%, while still keeping ~1.8 millin galaxies.

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

Dipole magnitude reduces to 0.014

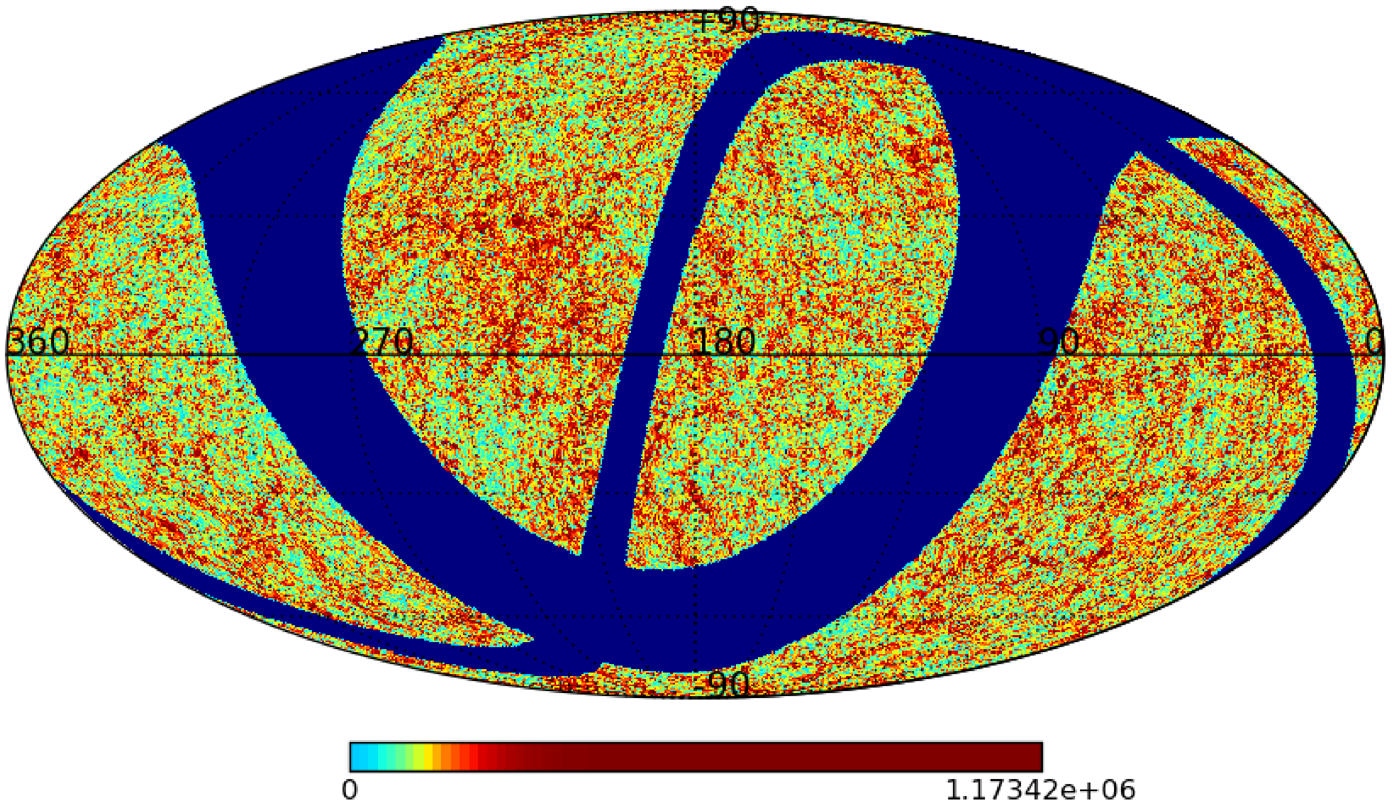
Star galaxy identification by cross correlating with SDSS

Suppressing local anisotropies

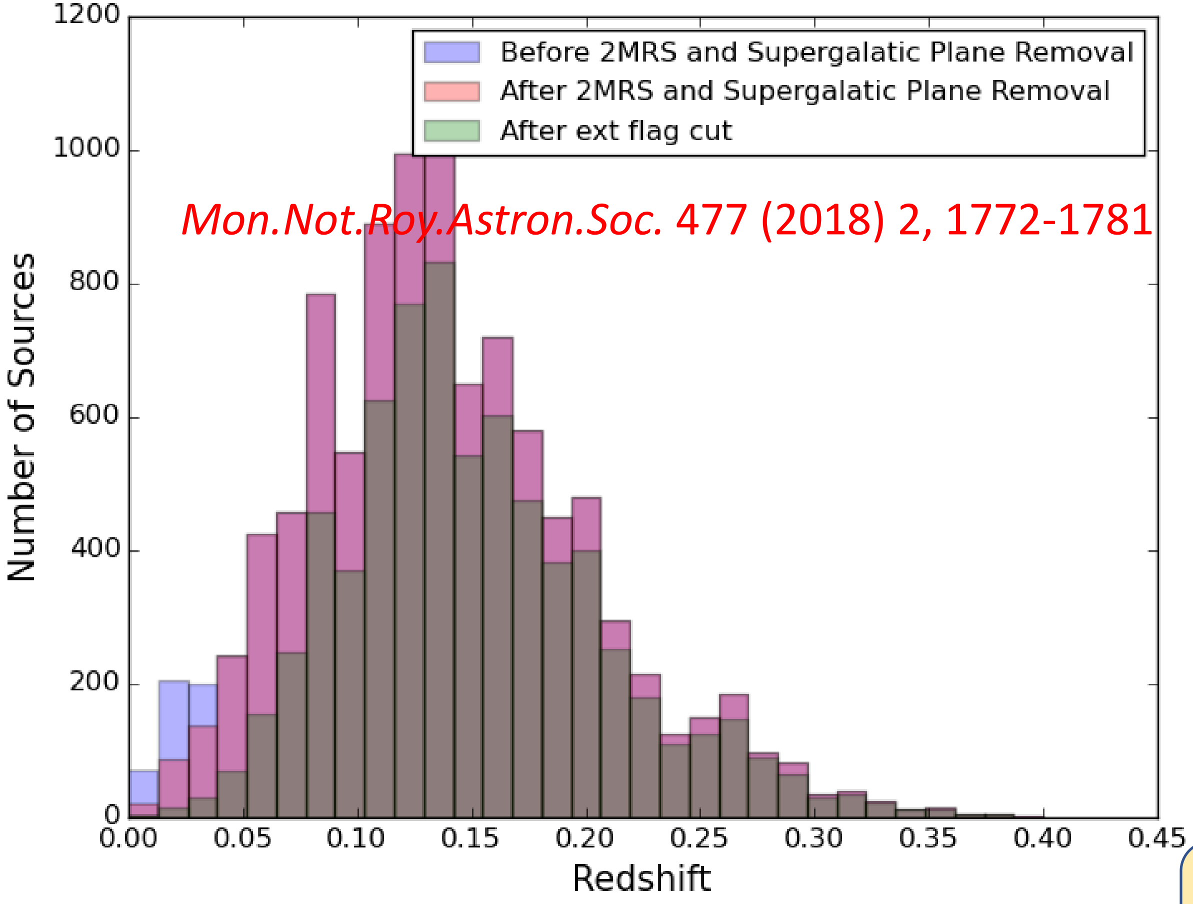


Remove extended sources and the supergalactic plane.

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

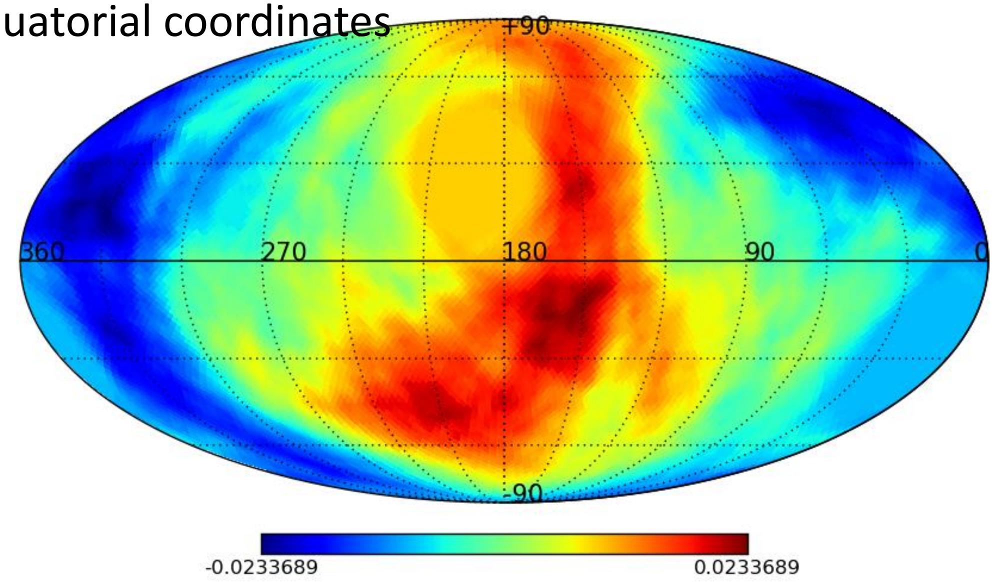
By cross correlating with Galaxy and Mass Assembly

d = 0.0124 > 3600 km/s if fully kinematic

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

4.6σ statistically significant.

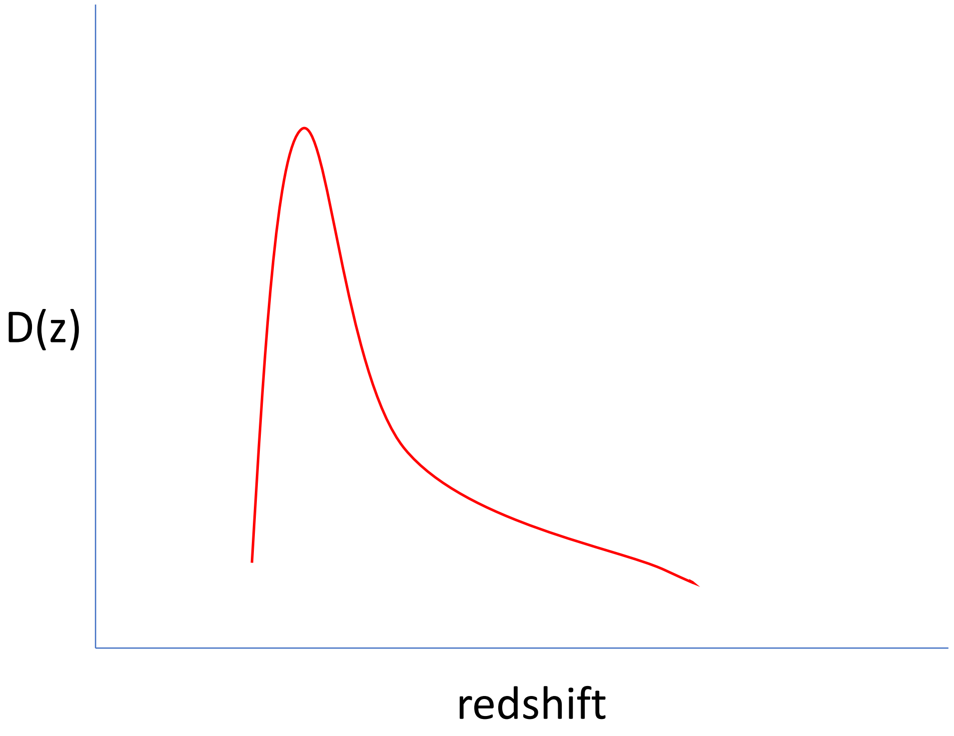
Equatorial coordinates



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

Dipoles in a catalogue of galaxies

In an all-sky catalogue with sources of redshift distribution D(z) from directionally unbiased survey with N sources



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

$\vec{\mathcal{K}}$ → **The Kinematic dipole,** depends on source spectrum, source flux function, observer velocity

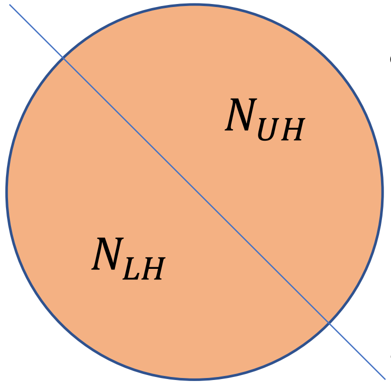
$\vec{\mathcal{R}}$ → **The shot noise dipole,** $\propto 1/\sqrt{N}$, isotropic

$\overrightarrow{D_{cls}}$ → **The clustering dipole,** local anisotropy due to structure

$\vec{\mathcal{F}}$ → **Foregrounds,** mainly stars and other Galactic contamination

Estimators for the Dipole

$$\vec{D}_H = \hat{z} * \frac{N_{UH} - N_{LH}}{N_{UH} + N_{LH}}$$



Vary the direction of the hemispheres until maximum asymmetry is observed

Easy visualization

High Bias and statistical error $2.6/\sqrt{N}$

$$\vec{D}_{3D} = \frac{1}{N}\sum_{i=1}^{N} \hat{r}_i$$

Add up unit vectors corresponding to directions in the sky for every source

Relatively lower bias and statistical error $1/\sqrt{N}$

Rubart and Schwarz 2013

$$\frac{\left[n_p \; - \bar{n}\left(1 + \vec{D}_q . \hat{r}_p\right)\right]^2}{\bar{n}\left(1 + \vec{D}_q . \hat{r}_p\right)}$$

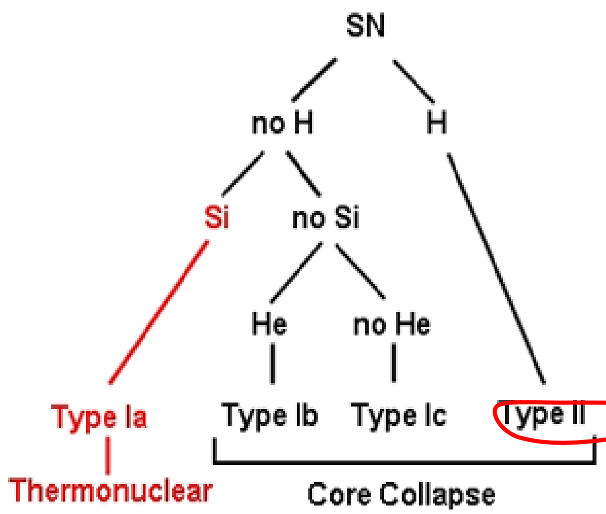
Minimize the above term, even less bias than the linear estimator

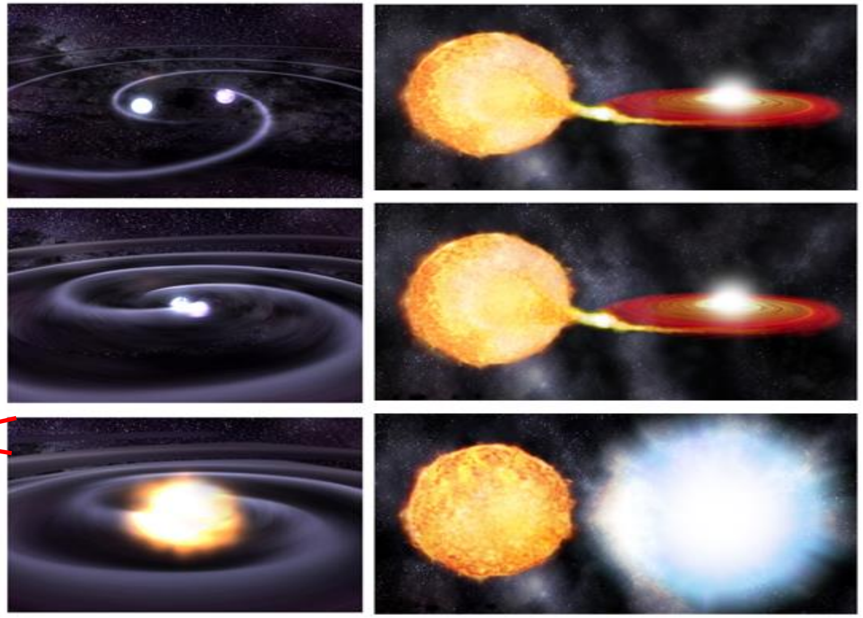
$$\vec{D}_H = \frac{\hat{z}}{N}\int_{\phi=0}^{\phi=2\pi}\int_{\theta=0}^{\theta=\pi} \sigma(\theta)\frac{|cos\theta|}{cos\theta} sin\theta d\theta d\phi$$

$$\vec{D}_C = \frac{\hat{z}}{N}\int_{\phi=0}^{\phi=2\pi}\int_{\theta=0}^{\theta=\pi} \sigma(\theta) cos\theta sin\theta d\theta d\phi$$

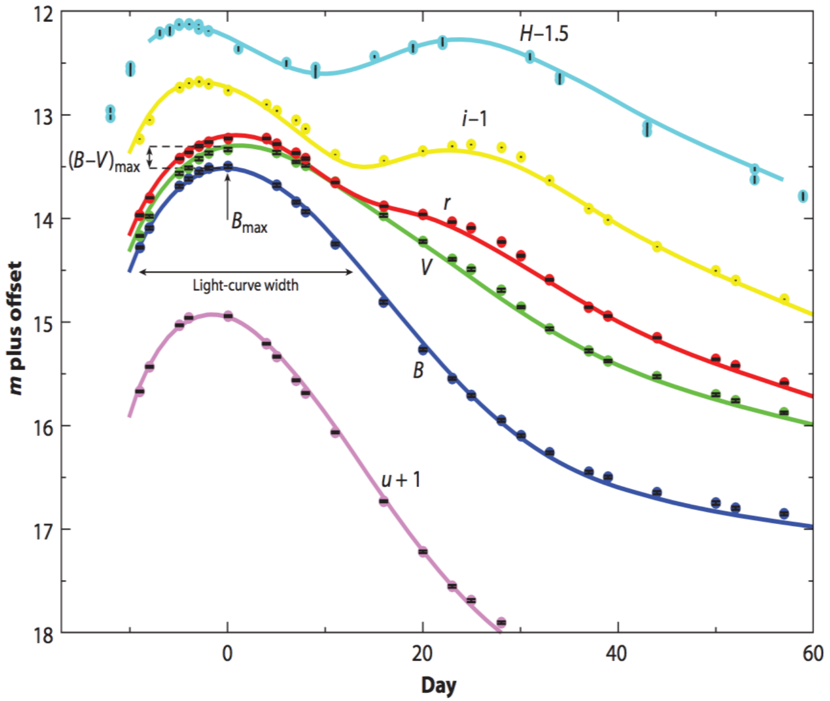
What are Type Ia supernovae?

Goobar & Leibundgut, arXiv:1102.1431

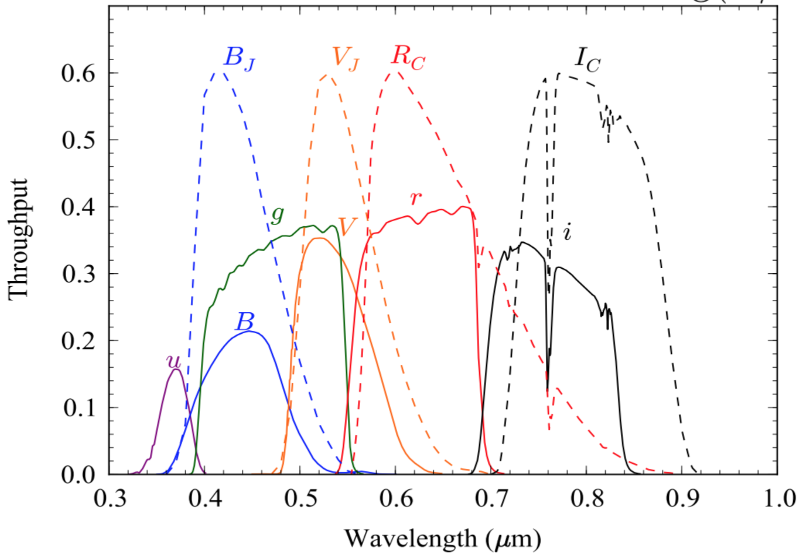




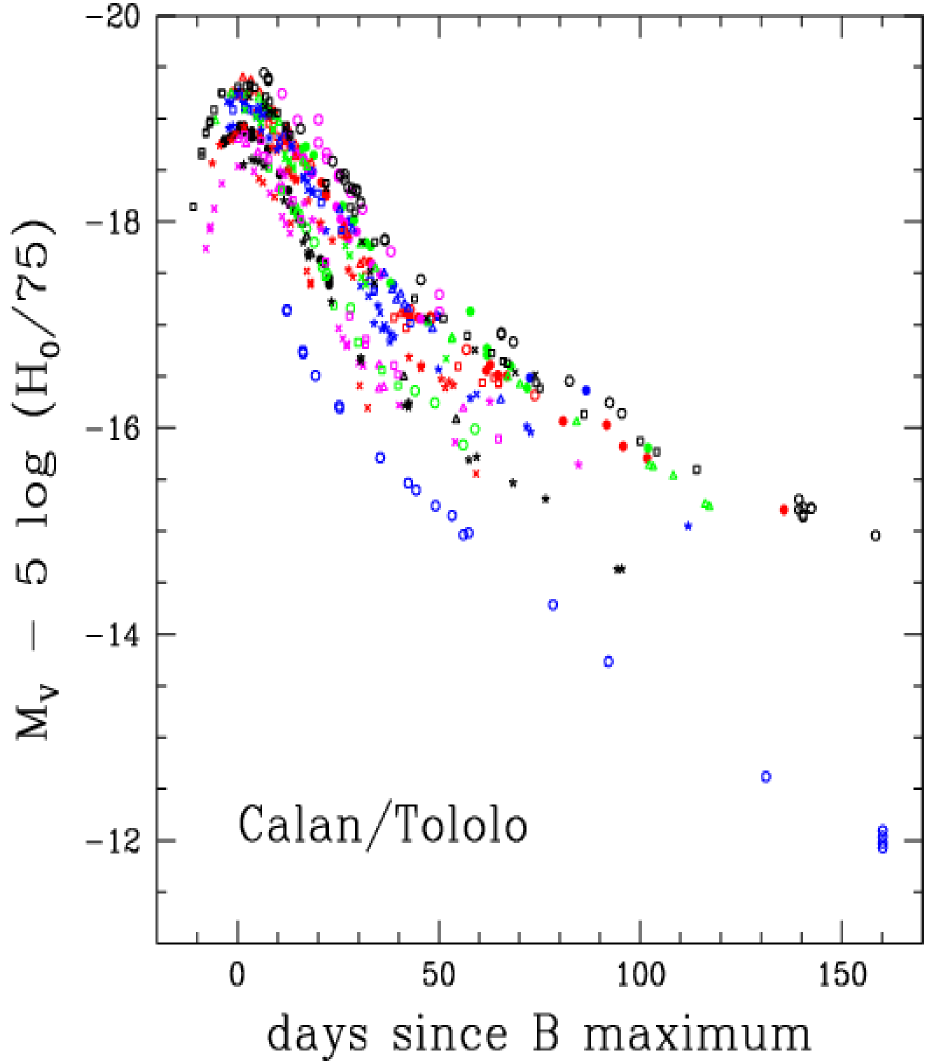
A white dwarf accreting matter from a binary companion, reignites when crossing ~1.44 Solar Masses



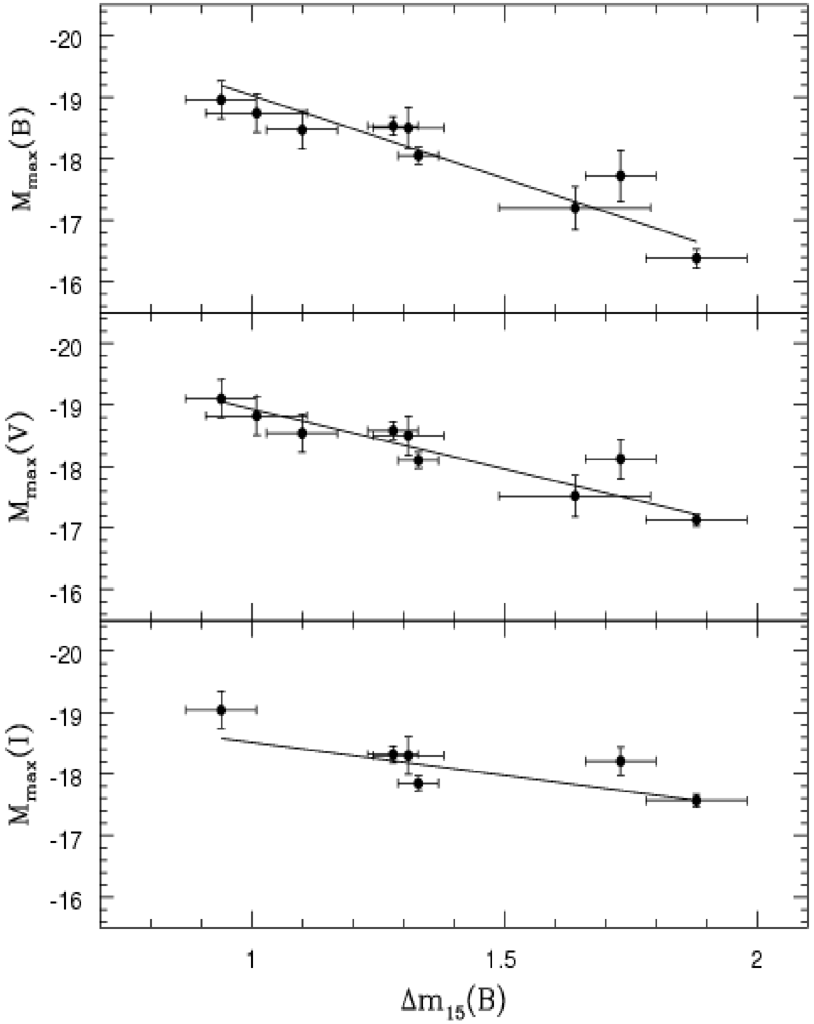
$$m = -2.5 \log(F/F_{\mathrm{ref}})$$



They are certainly *not* ‘standard candles’



Hamuy, arXiv:311.5099

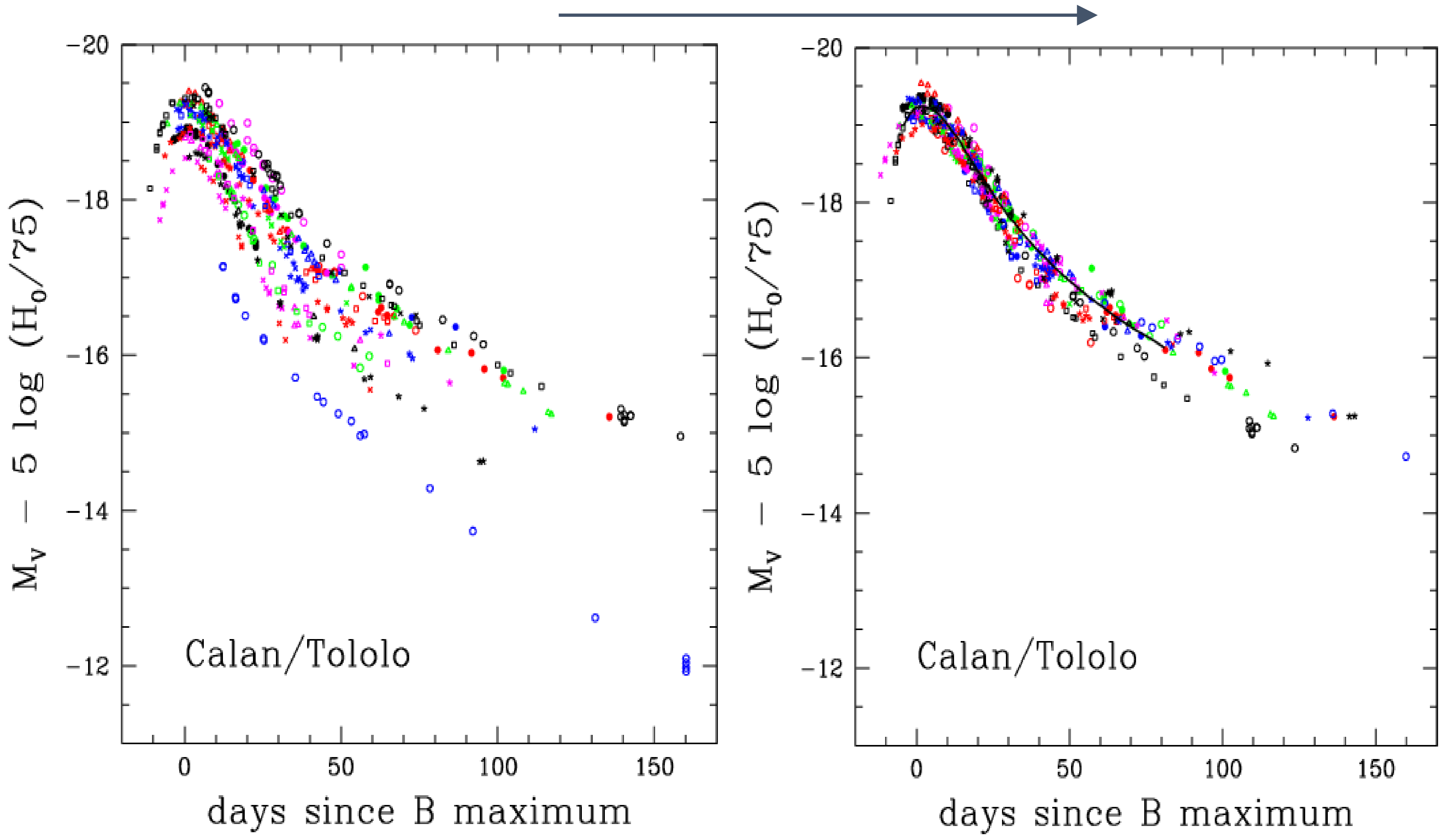


Phillips, ApJ **413**:L105, 1993

But they can be ‘standardised’ using the observed correlation between their peak magnitude and light-curve width (NB: this is *not* understood theoretically)

Type Ia supernovae as ‘standardisable candles’

Corrected data

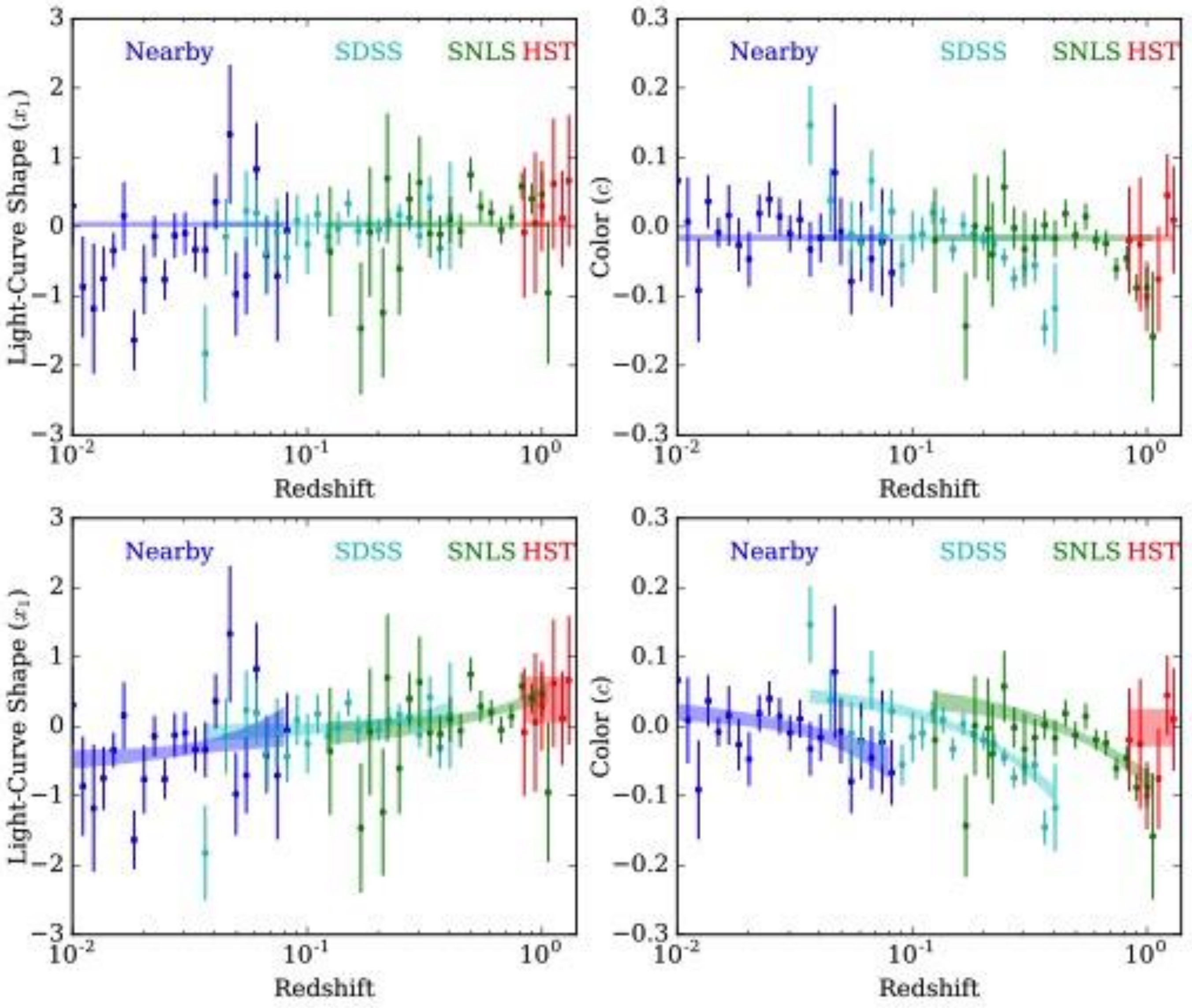


Hamuy, 1311.5099

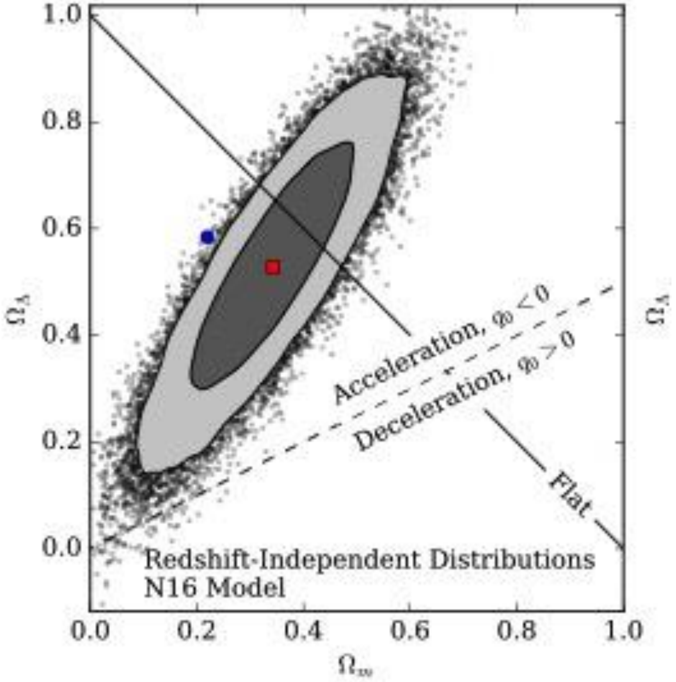
Distance modulus $$\mu_B = m_B^* - M + \alpha X_1 - \beta \mathcal{C}$$ $$= 25 + 5 \log_{10} \frac{d_L}{Mpc}$$

Use a standard template (e.g. SALT 2) to make ‘stretch’ and ‘colour’ corrections …

Issue 1: Rubin & Heitlauf 2019, Rubin & Hayden 2016

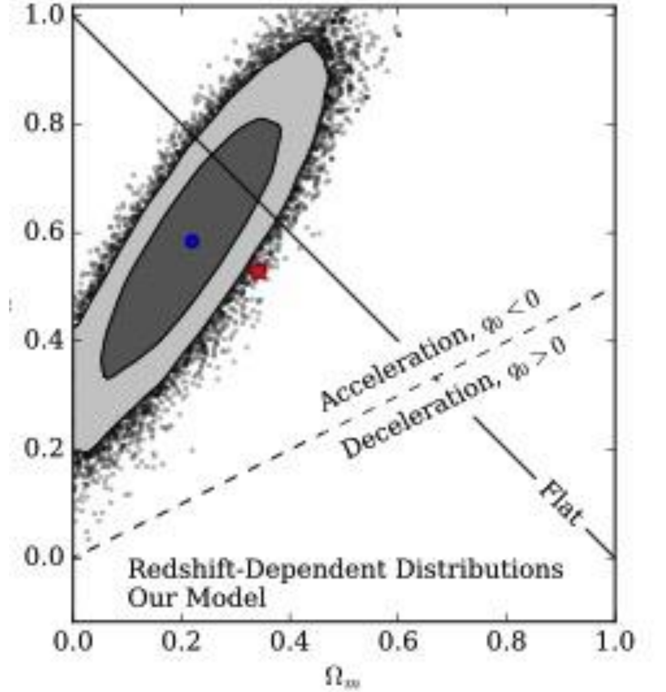


$$\mu_B = m_B^* - M + \alpha X_1 - \beta \mathcal{C}$$



Dam *et al*

Rahman *et al*



But if x_1 and c are z-dependent, SNe Ia are not standardizeable

See also works by Young-Wook Lee