Falsifying the standard model of cosmology

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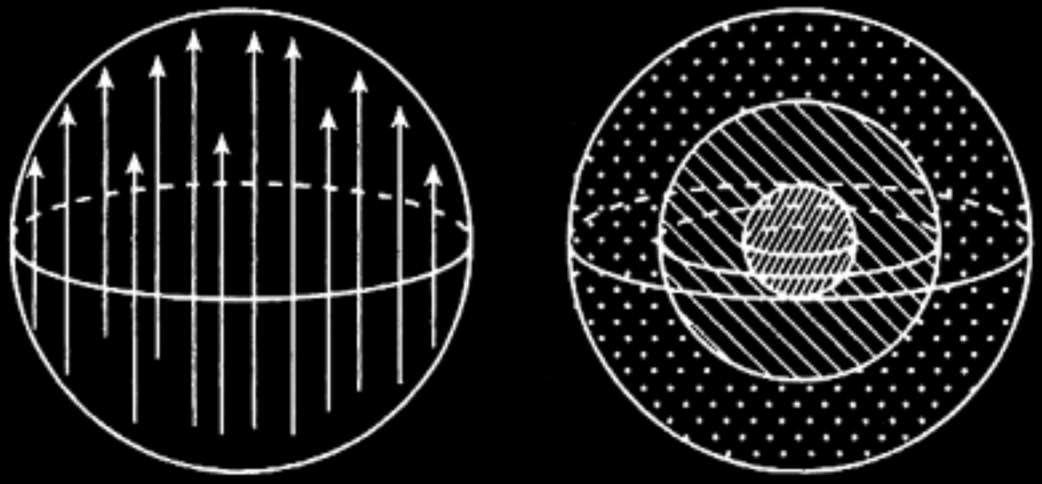
work in coll with:

Secrest, von Hausegger, Colin, Mohayaee, Sarkar

XXV DAE-BRNS High Energy Physics Symposium 2022, Mohali

The cosmological principle

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



Homogeneous
Not isotropic

Isotropic
Not homogeneous

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

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

The real reason, though, for our adherence here to the Cosmological Principle is not that it is surely correct, but rather, that it allows us to make use of the extremely limited data provided to cosmology by observational astronomy. …

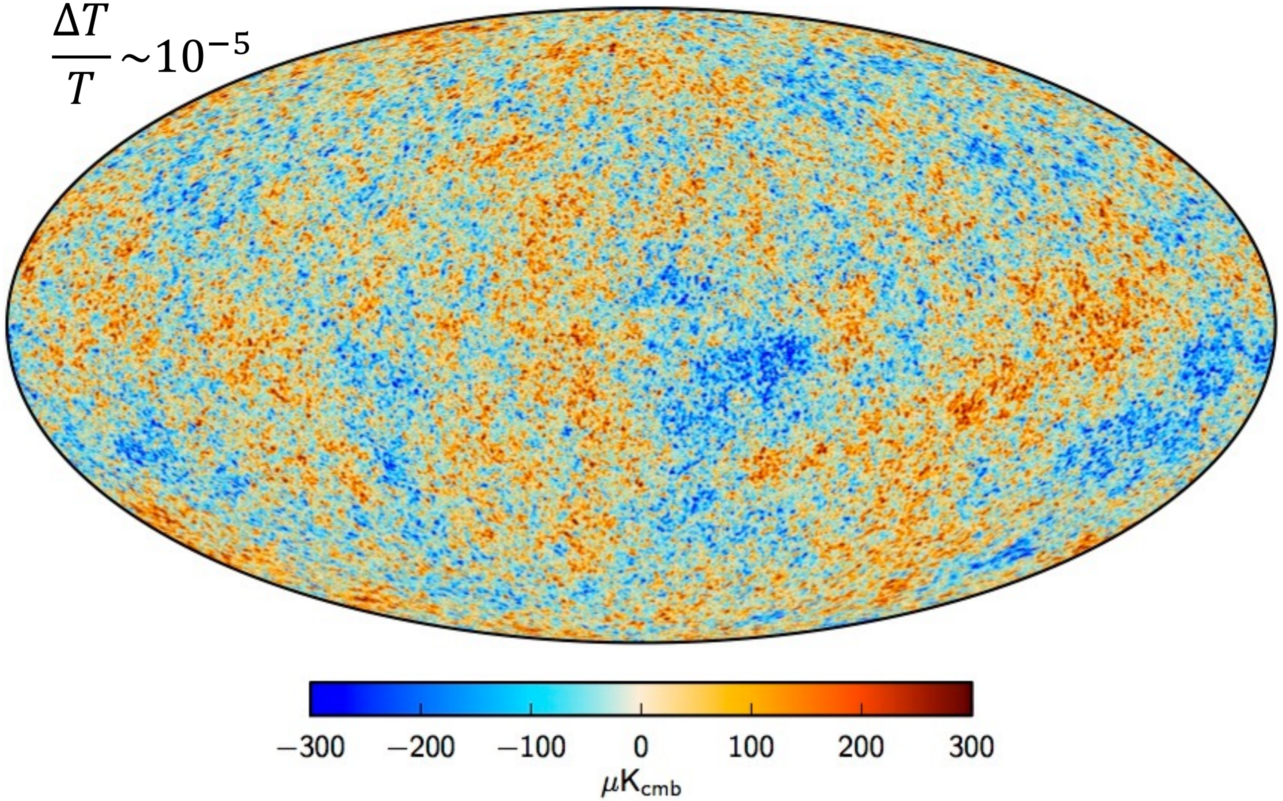
… If the data will not fit into this framework, we shall be able to conclude that either the Cosmological Principle or the Principle of Equivalence is wrong. Nothing could be more interesting.

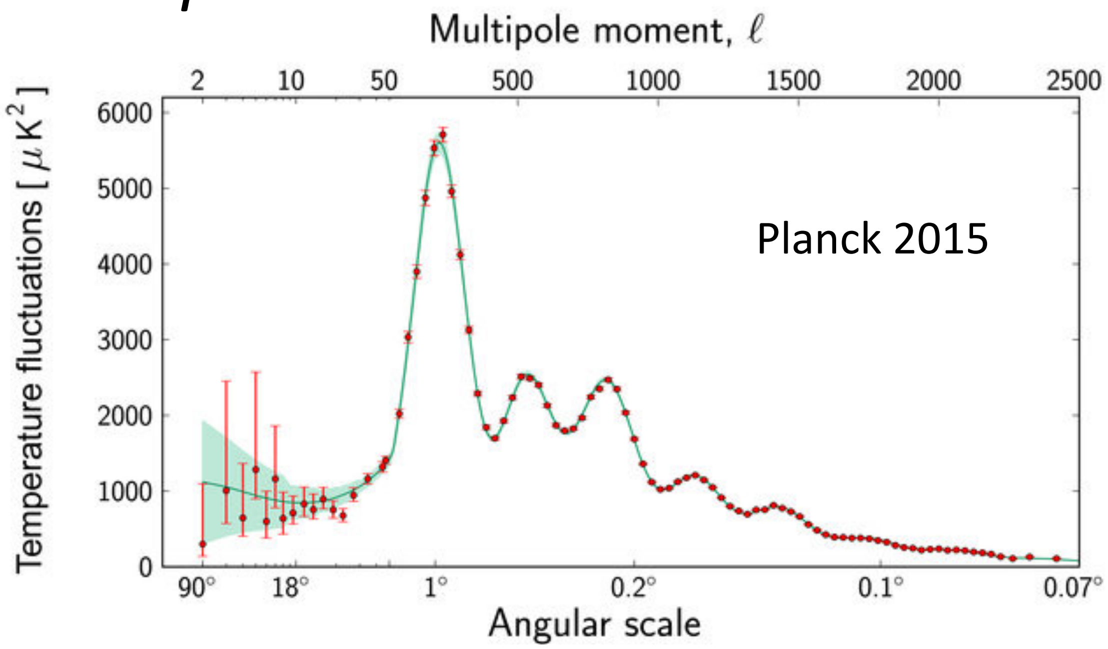
Steven Weinberg, *Gravitation and Cosmology* (1972)

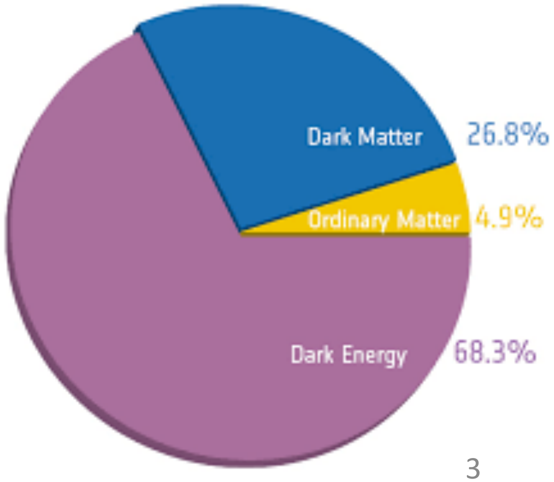
"Data from the Planck satellite show the Universe to be highly isotropic"

T = 2.725 K

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

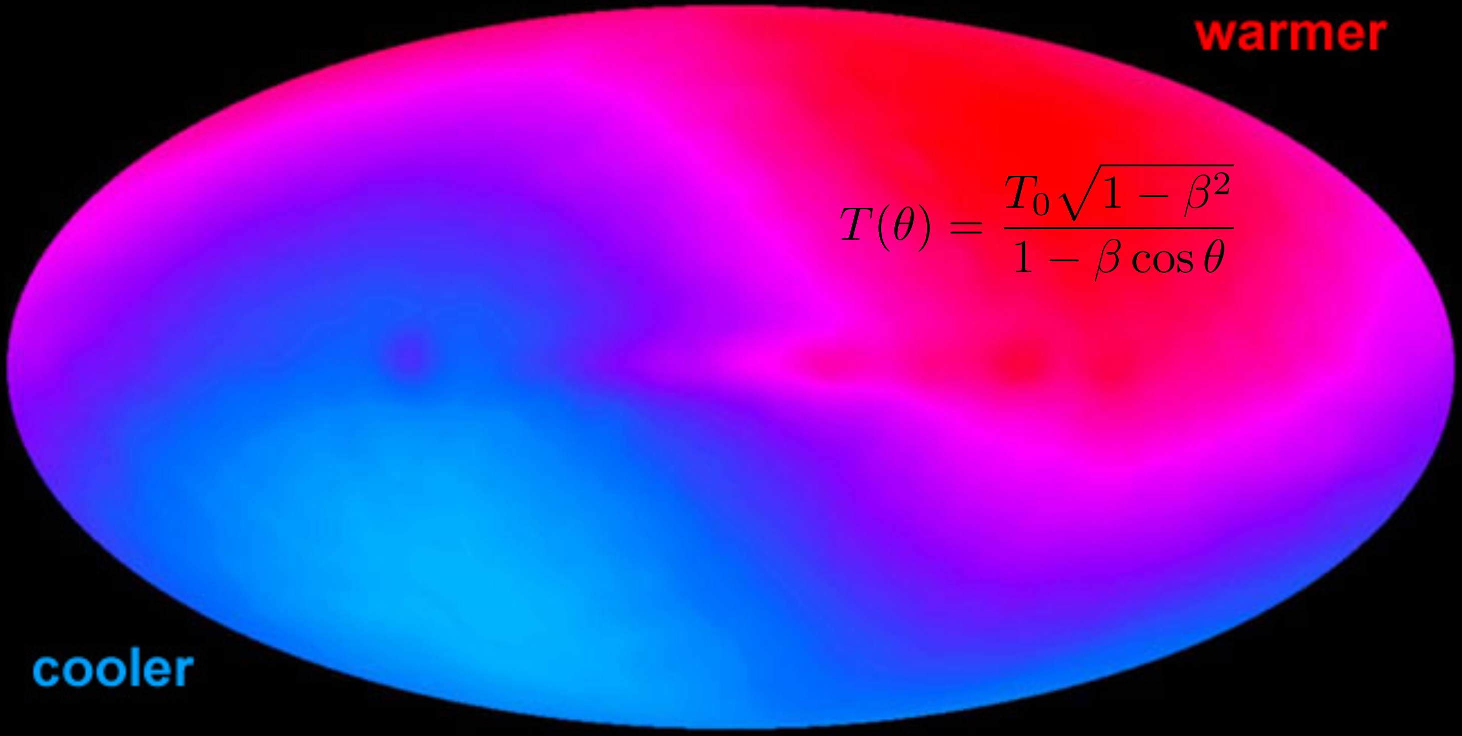






We observe a statistically isotropic Gaussian random field of small temperature fluctuations (fully quantified by the 2-point correlations ➛ angular power spectrum)

The CMB Dipole : Purely Kinematic?



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

COBE Experiment, 1996
Planck 2015

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

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

R.A = 168.0, DEC = -7.0

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

Is this 'Purely Kinematic'?

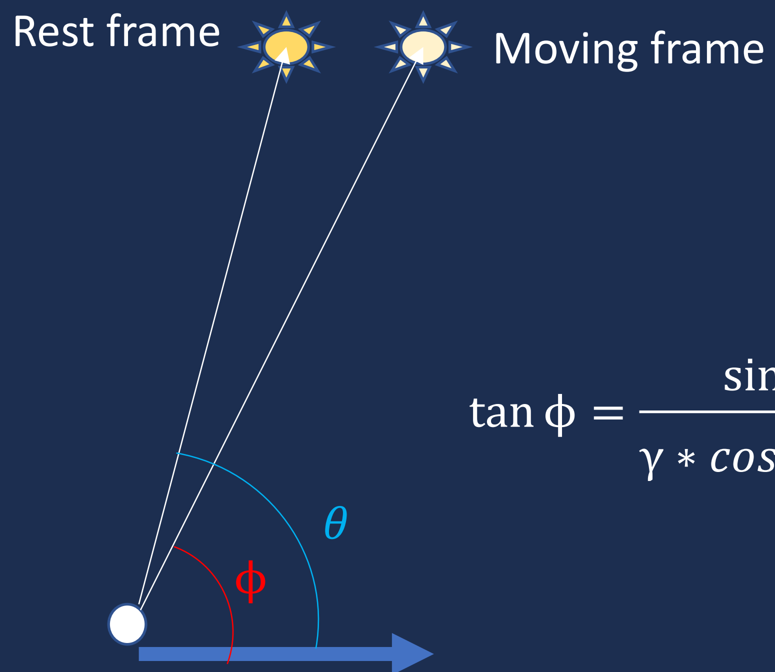
What is the origin of this motion?

A moving observer - Kinematic Dipole

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

Ellis & Baldwin (1984)

Aberration



Observer, velocity v

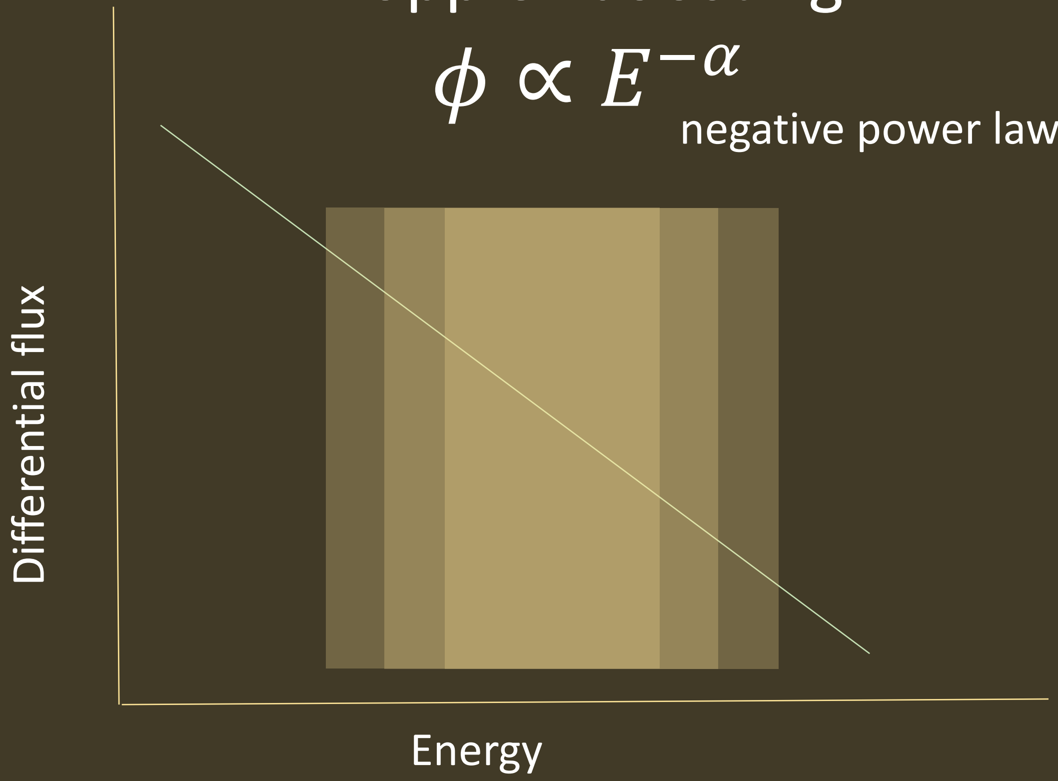
$$\tan\phi = \frac{\sin\theta}{\gamma * cos\theta - \frac{v}{c}}$$

+

Doppler boosting

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

negative power law



Flux limited catalog -> more sources in direction of motion

On the expected anisotropy of radio source counts

G. F. R. Ellis★ and J. E. Baldwin† *Orthodox Academy of Crete, Kolymbari, Crete*

Received 1983 May 31; in original form 1983 March 31

Summary. If the standard interpretation of the dipole anisotropy in the microwave background radiation as being due to our peculiar velocity in a homogeneous isotropic universe is correct, then radio-source number counts must show a similar anisotropy. Conversely, determination of a dipole anisotropy in those counts determines our velocity relative to their rest frame; this velocity must agree with that determined from the microwave background radiation anisotropy. Present limits show reasonable agreement between these velocities.

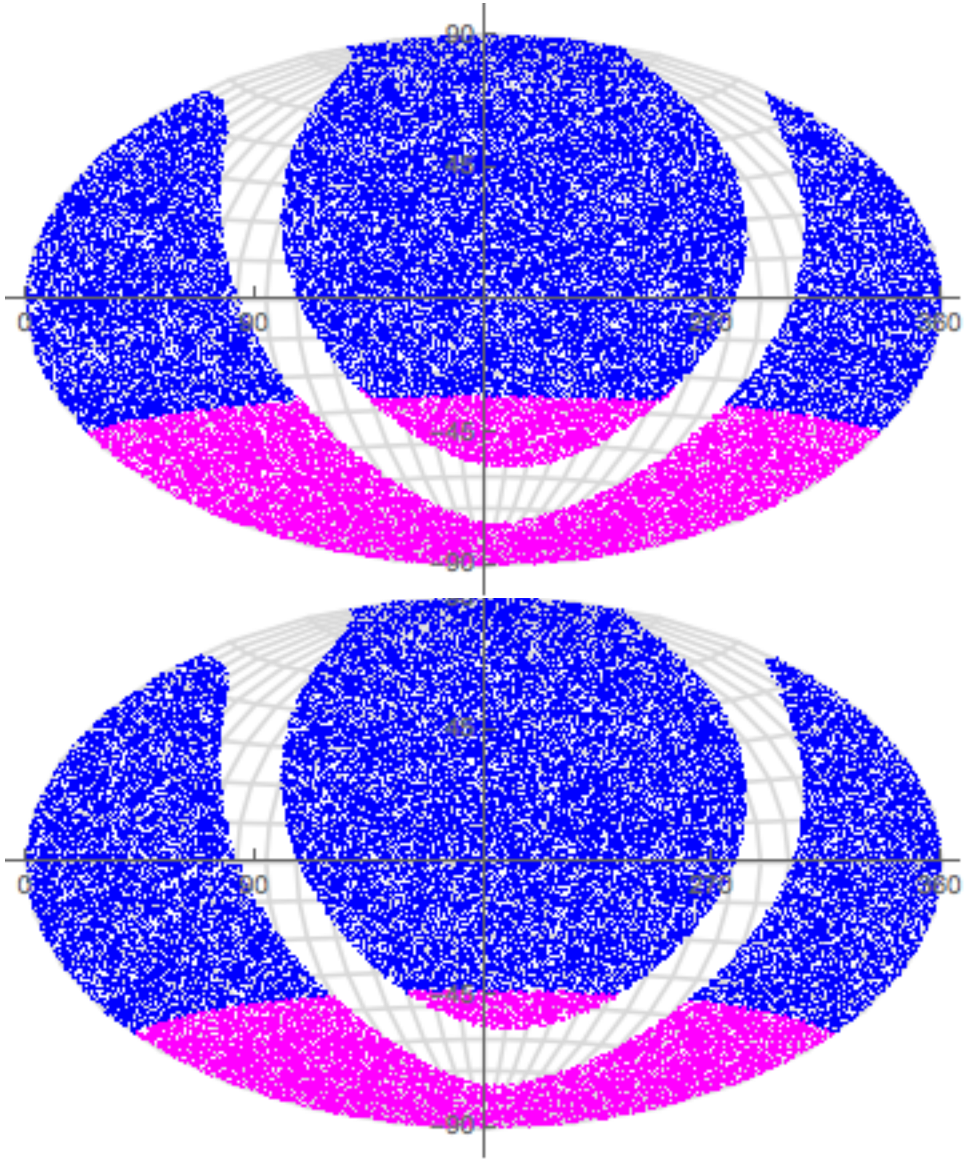
4 Conclusion

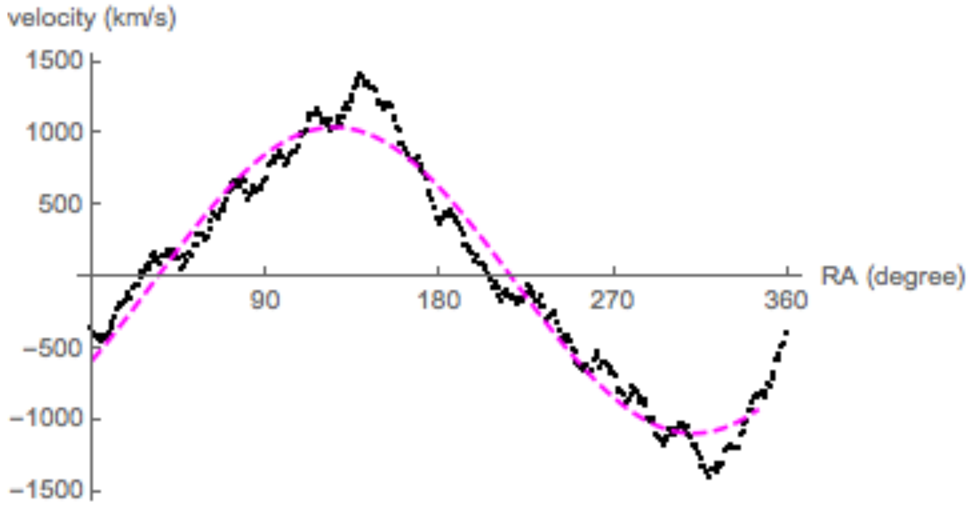
Anisotropies in radio-source number counts can be used to determine a cosmological standard of rest. Current observations determine it to about $\pm 500\ \mathrm{km\ s^{-1}}$, but accurate counts of fainter sources will reduce the error to a level comparable to that set by observations of the microwave background radiation. If the standards of rest determined by the MBR and the number counts were to be in serious disagreement, one would have to abandon either

(a) the idea that the radio sources are at cosmological distances, or
(b) the interpretation of the cosmic microwave radiation as relic radiation from the big bang, or
(c) the standard FRW Universe models.

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

The NVSUMSS-Combined All Sky catalog





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 !

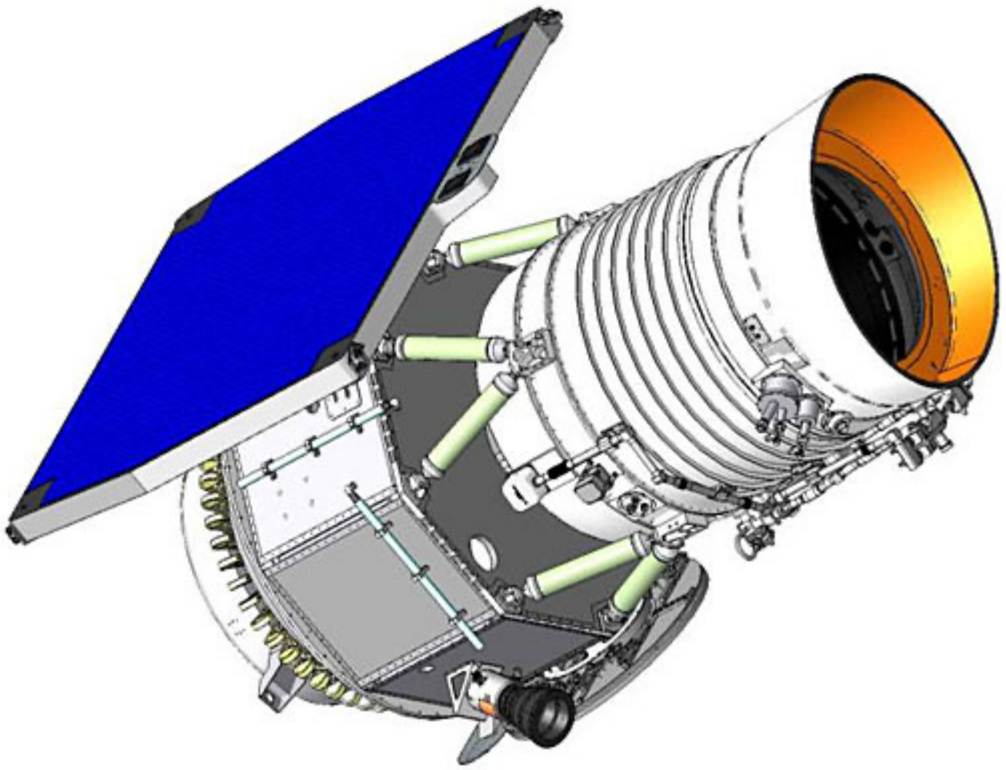
SKA phase 1 measurement ~10%

Bengaly (et al) 2018 :

Siewert et al 2020

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

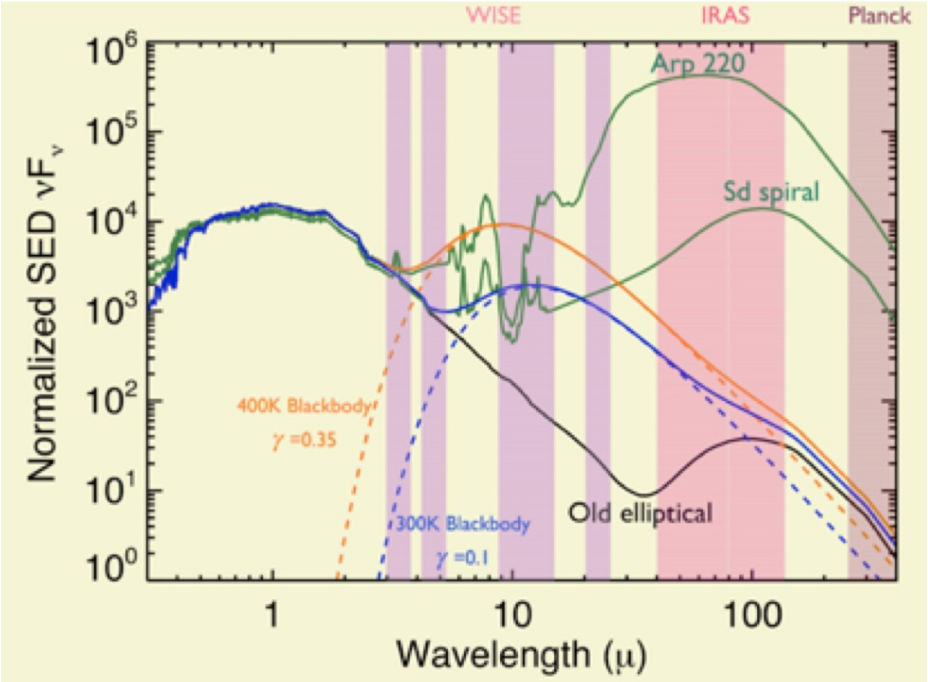
The Widefield Infrared Survey Explorer



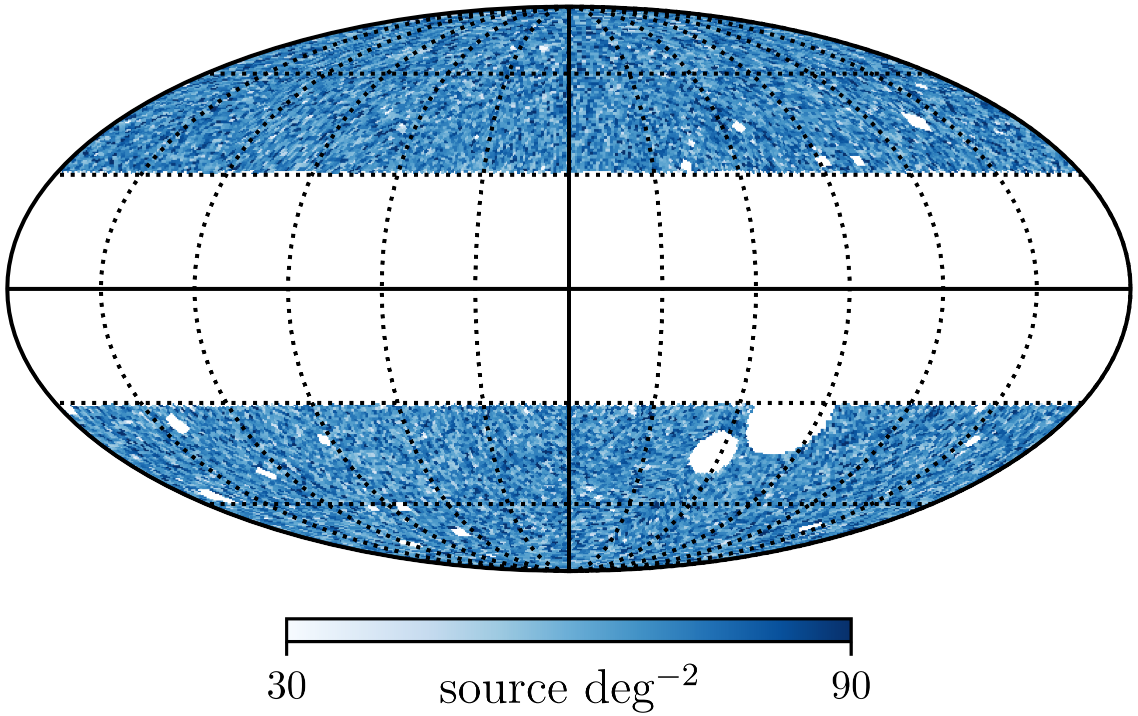
All sky infrared survey over 10 months, in the bands 3.4, 4.6, 12 and 22 μm using a 40 cm diameter telescope

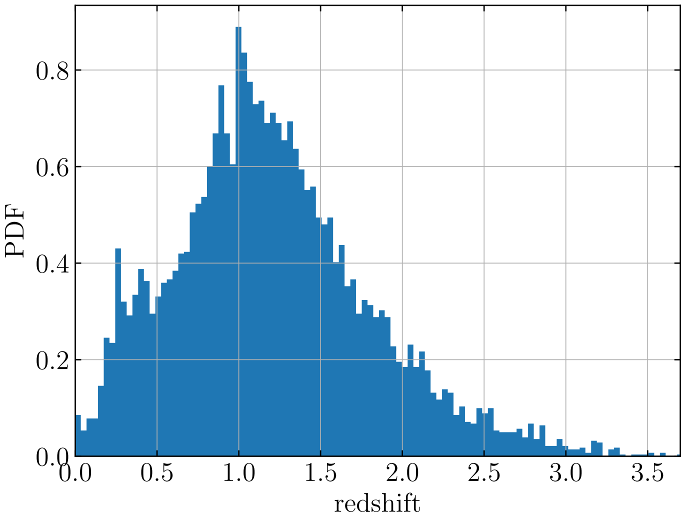
Generated a catalog of 746 million+ objects, most of which are stars.

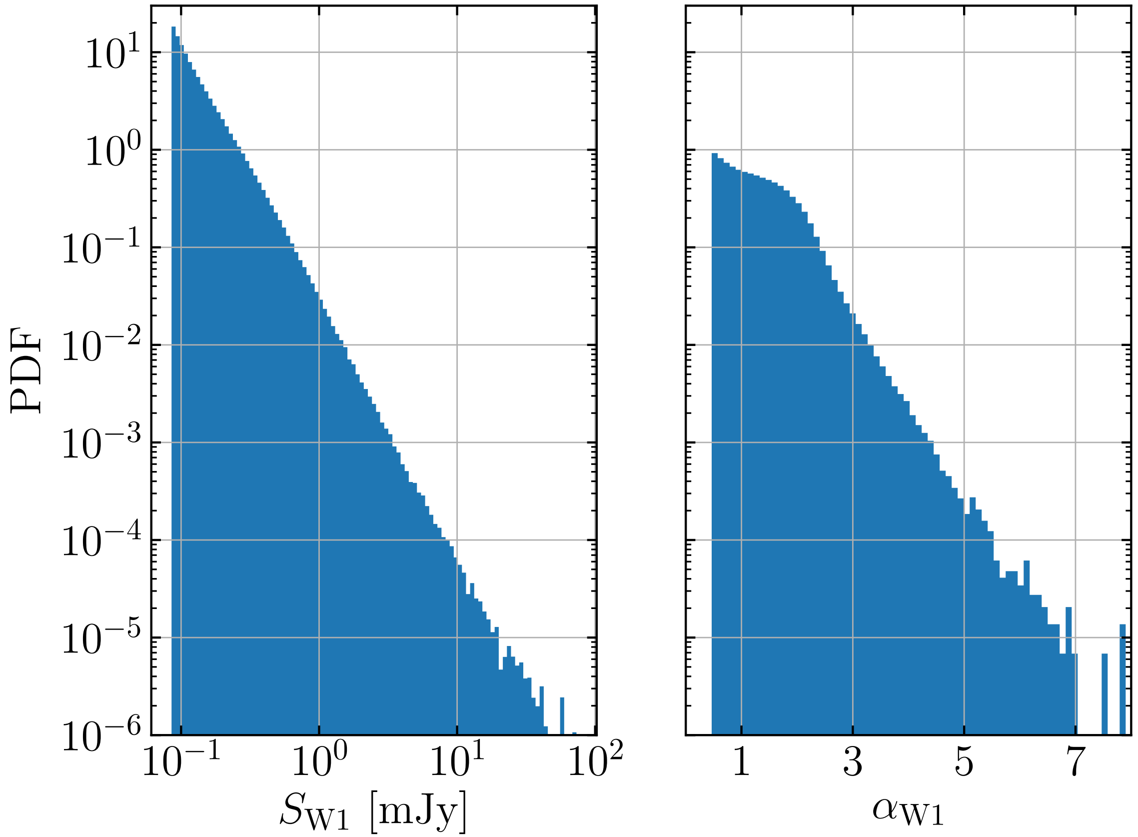
Directionally unbiased survey strategy, arc second angular resolution, multi band photometry.



CatWISE AGN 1355352 sources

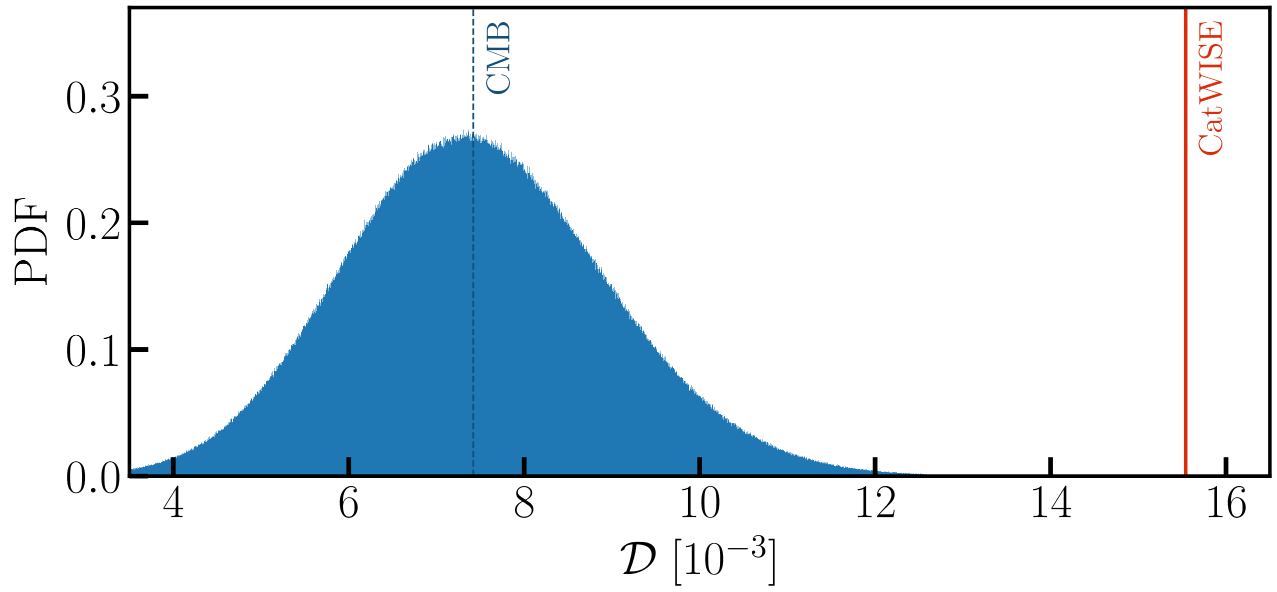


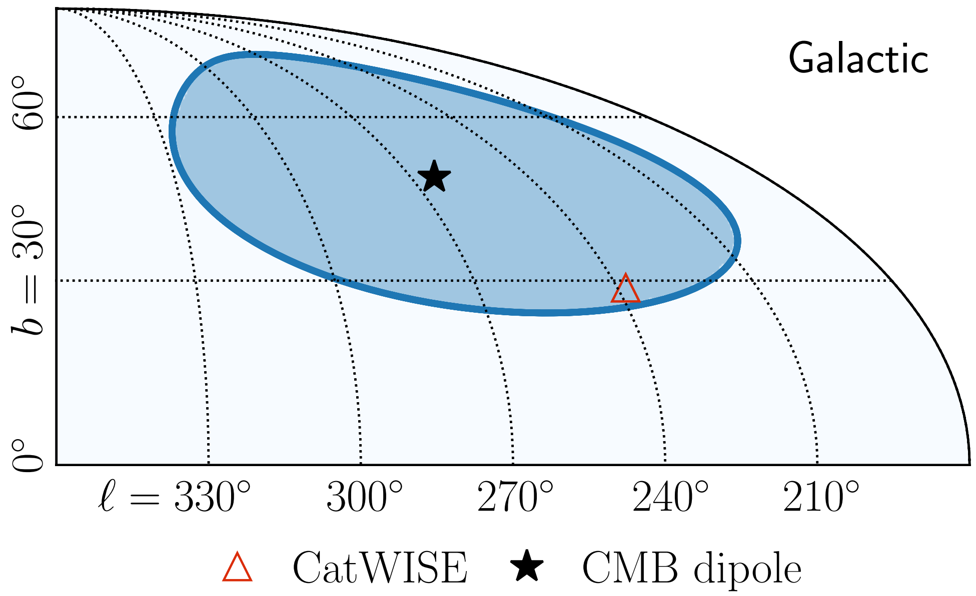




Astrophys.J.Lett. 908 (2021) 2, L51

Results

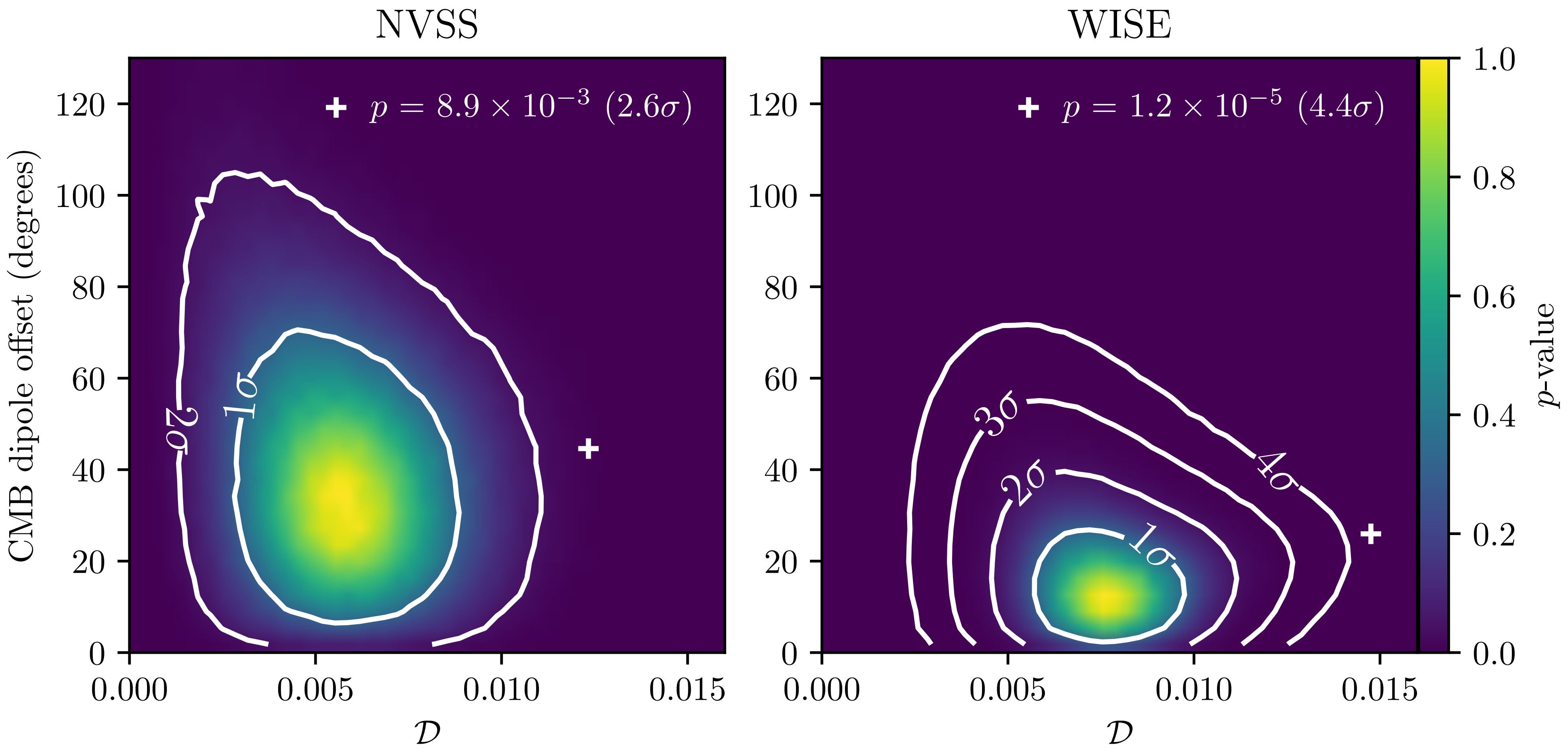




p = 5 $\times 10^{-7}$ (4.9 σ)

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

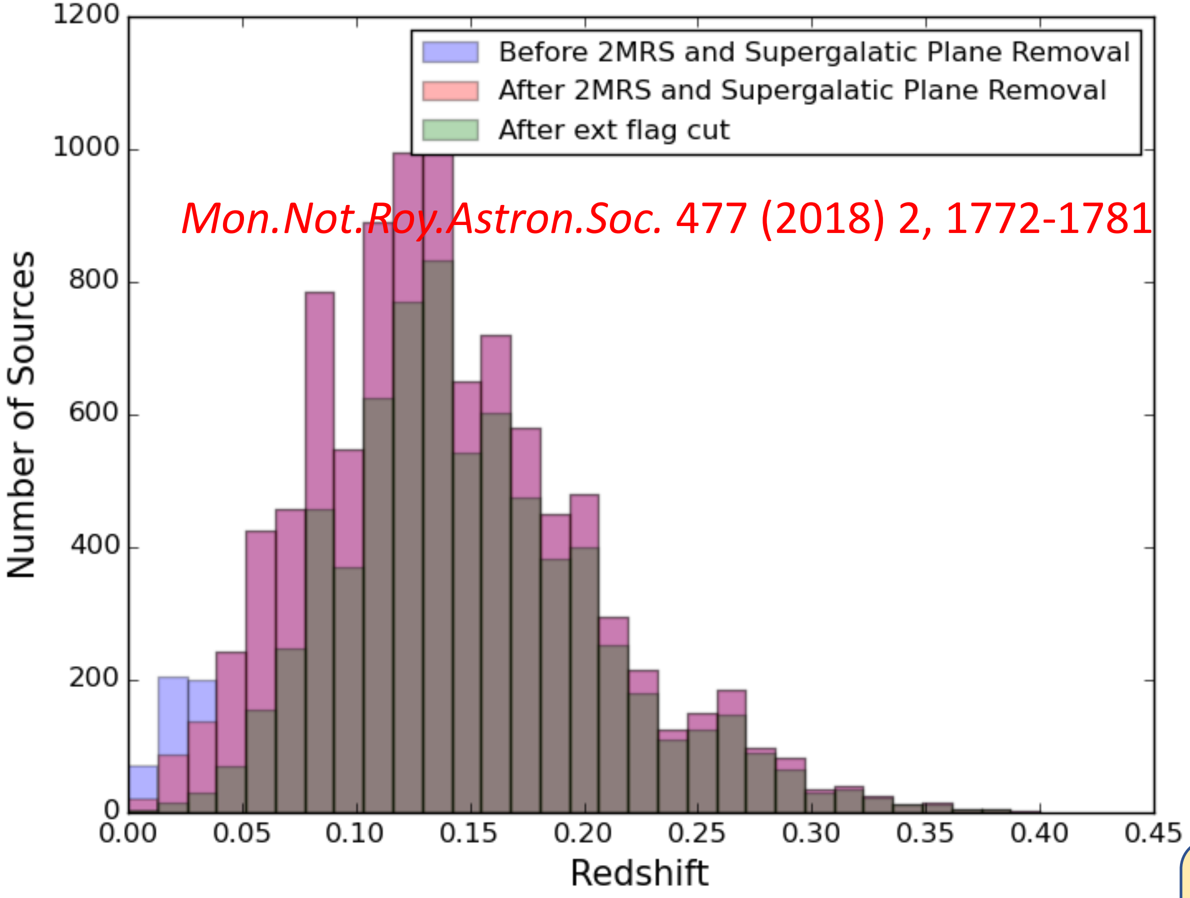
https://zenodo.org/record/4448512



Conservative Sample size weighted Z-scores : 5.1 σ

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

1192182 - AllWISE Galaxies



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

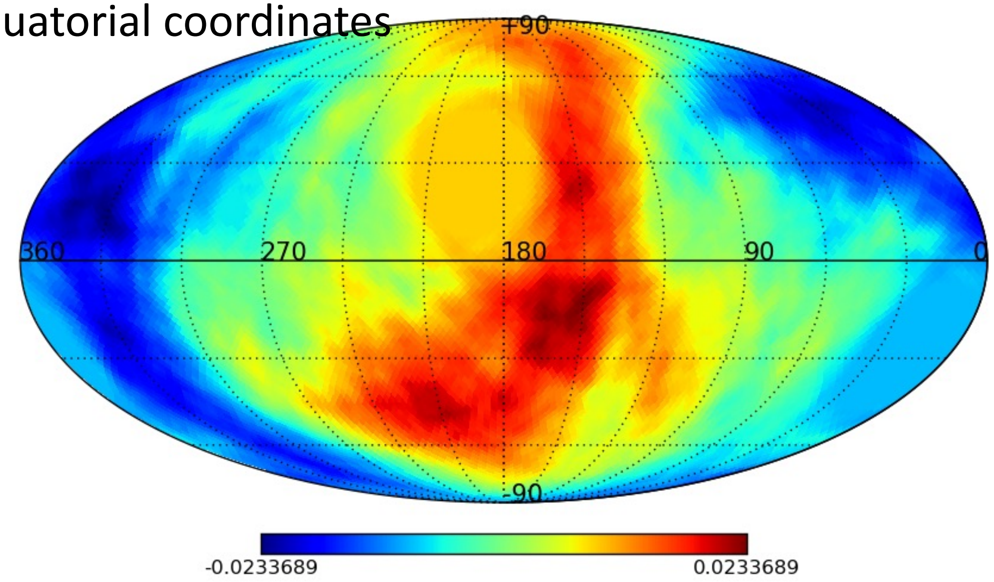
By cross correlating with Galaxy and Mass Assembly

d = 0.0124 > 3600 km/s if fully kinematic

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

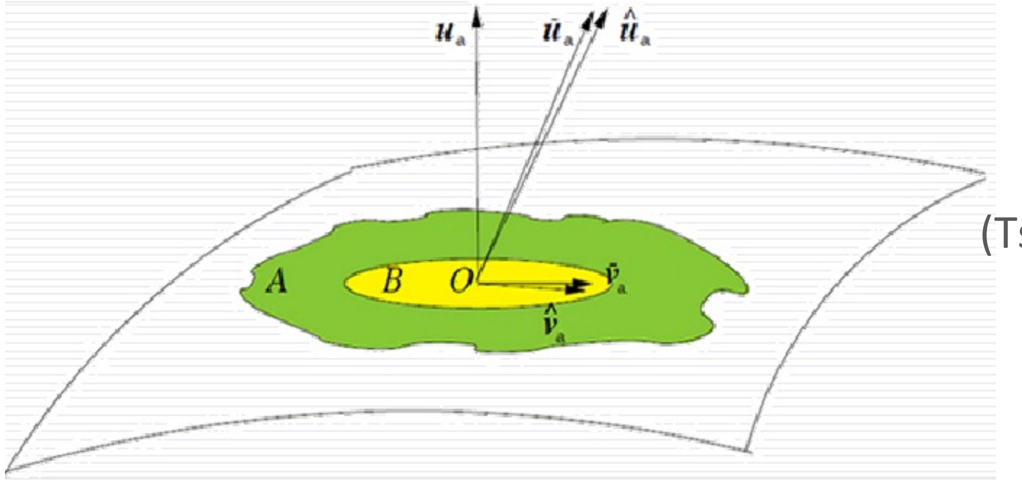
4.6σ statistically significant.

Equatorial coordinates



V = 1260 ± 629 km/s within 6 degrees of CMB dipole
Low redshift

The tilted Friedmann Universe



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

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

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

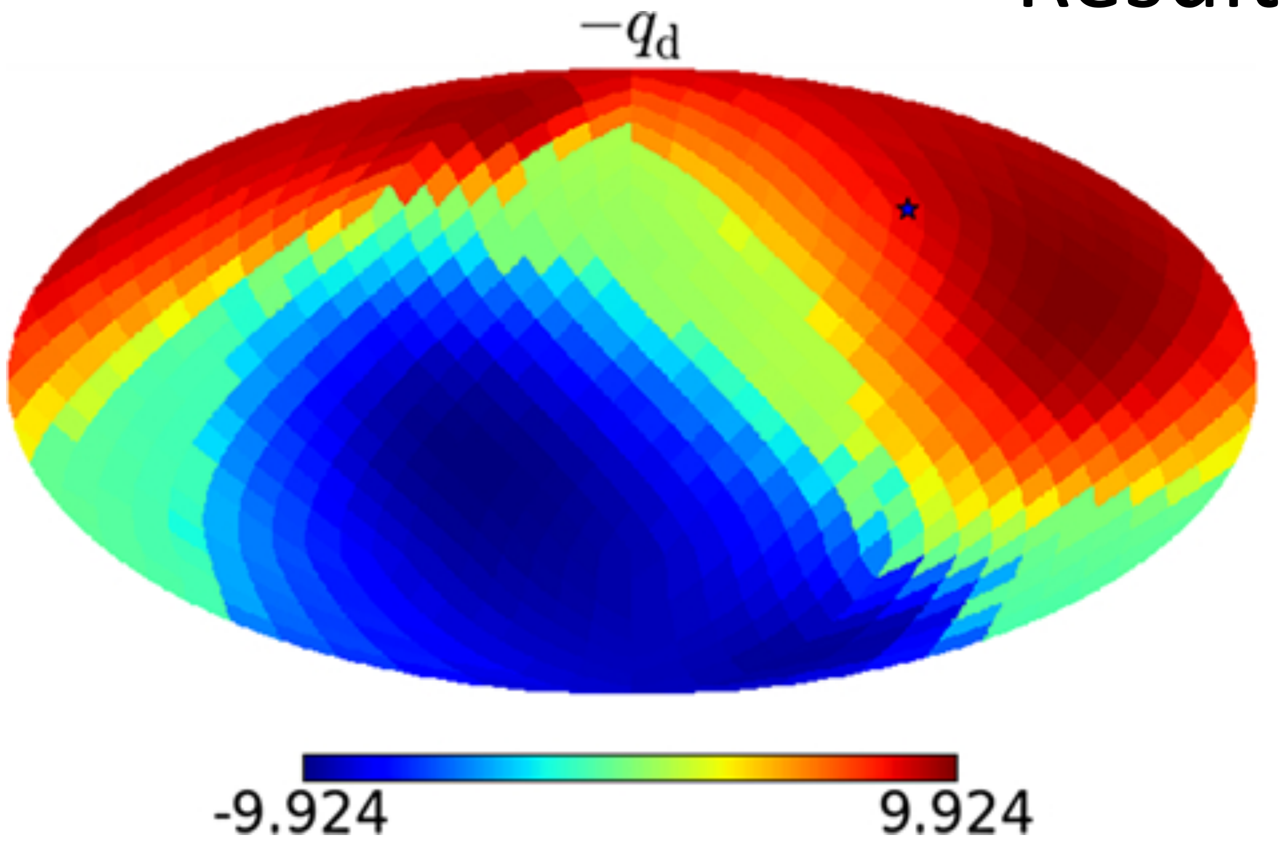
$$\tilde{\Theta} = \Theta + \vartheta,$$

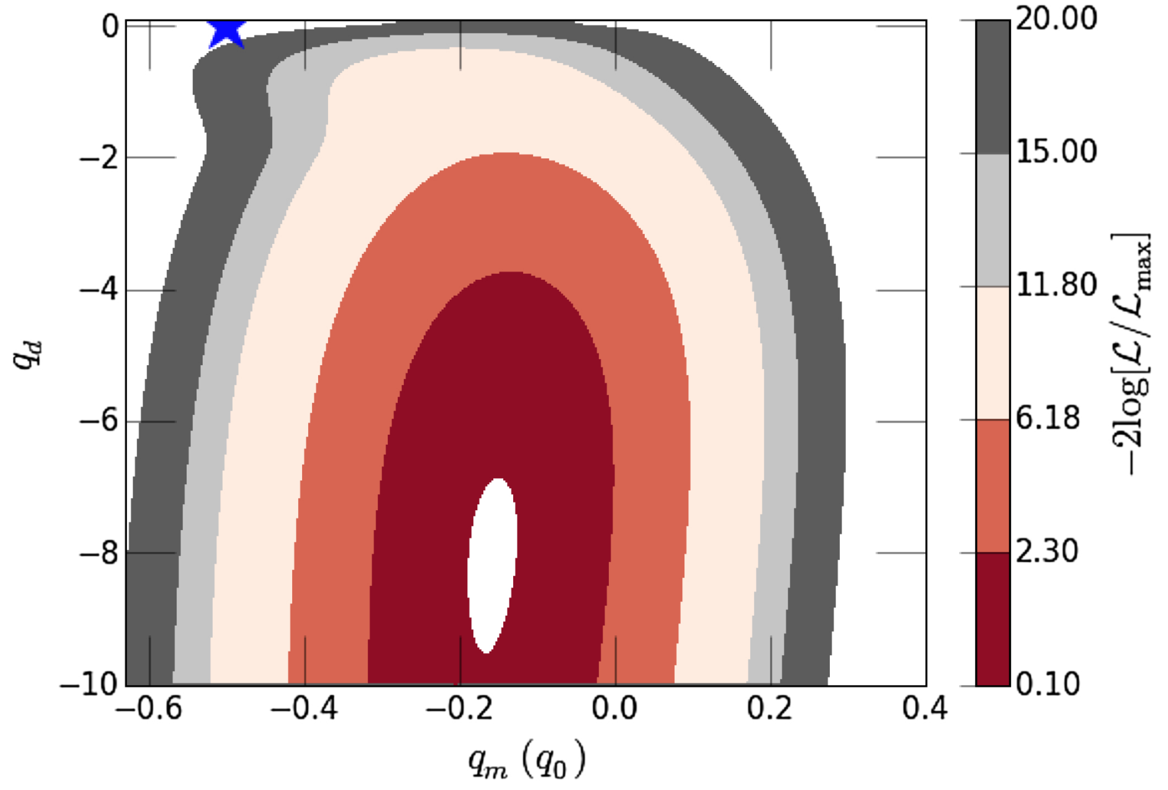
$$1 + \tilde{q} = (1+q)\left(1+\frac{\vartheta}{\Theta}\right)^{-2} - \frac{3\dot{\vartheta}}{\Theta^2}\left(1+\frac{\vartheta}{\Theta}\right)^{-2},$$

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.**

Results





https://github.com/rameez3333/Dipole_JLA

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

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

Dipole Statistically significant at 3.9 σ level

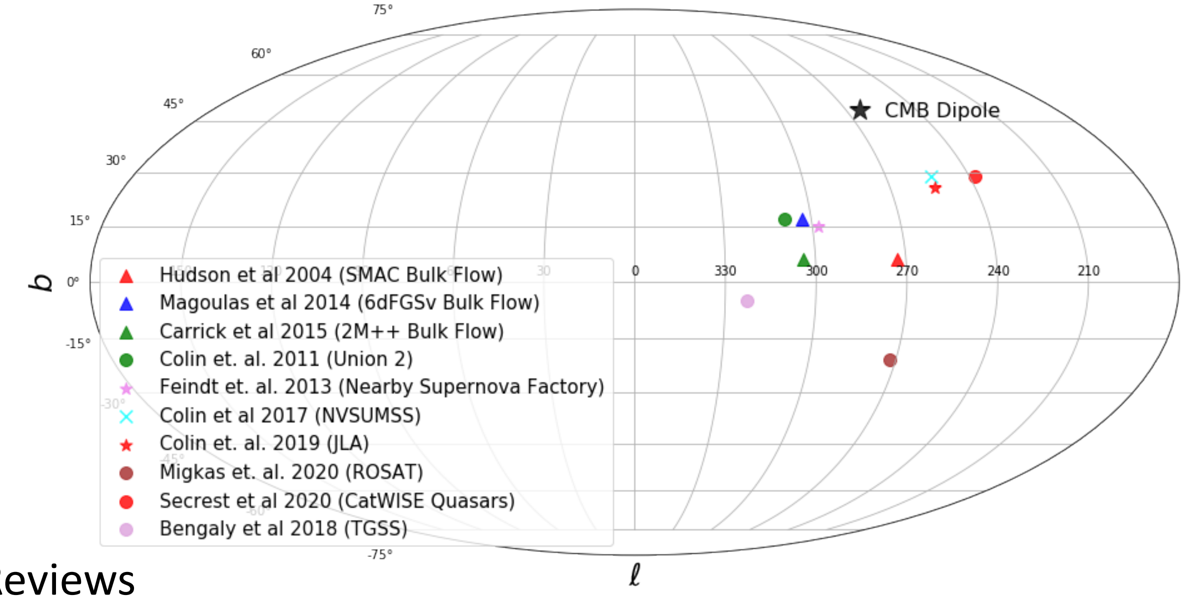
In agreement with the predictions by Tsagas,

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

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

Conclusions

- Ellis & Baldwin tests performed on Radio galaxy catalogues and WISE Quasars conclusively reject the exclusively kinematic interpretation of the CMB dipole at $> 5\,\sigma$. CMB rest frame and matter rest frame are different. Cosmological principle has been falsified.
- SN1a data are better fit by a "tilted Friedmann model". Ensuing debate stultifies dark energy evidence.
- Strong hint towards the inhomogeneous cosmological models.
- Highlighted by Peebles in his review of anomalies in physical cosmology.
- 300+ citations, Quanta Magazine, New Scientist
- Stultifies the Hubble tension:
  - *M.R. and Subir Sarkar, Class.Quant.Grav.* 38 (2021) 15, 154005
- Requires a Bianchi cosmology
  - Krishnan et al arxiv:2209:14918



Reviews

Mohayaee, Rameez & Sarkar

Eur.Phys.J.ST 230 (2021) 9, 2067-2076

Subir Sarkar

"Heart of Darkness"

Inference: International Review of Science 6 (2022) 4

Three projects in LSST DESC

All who have data access are welcome to join

This talk:

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

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

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

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

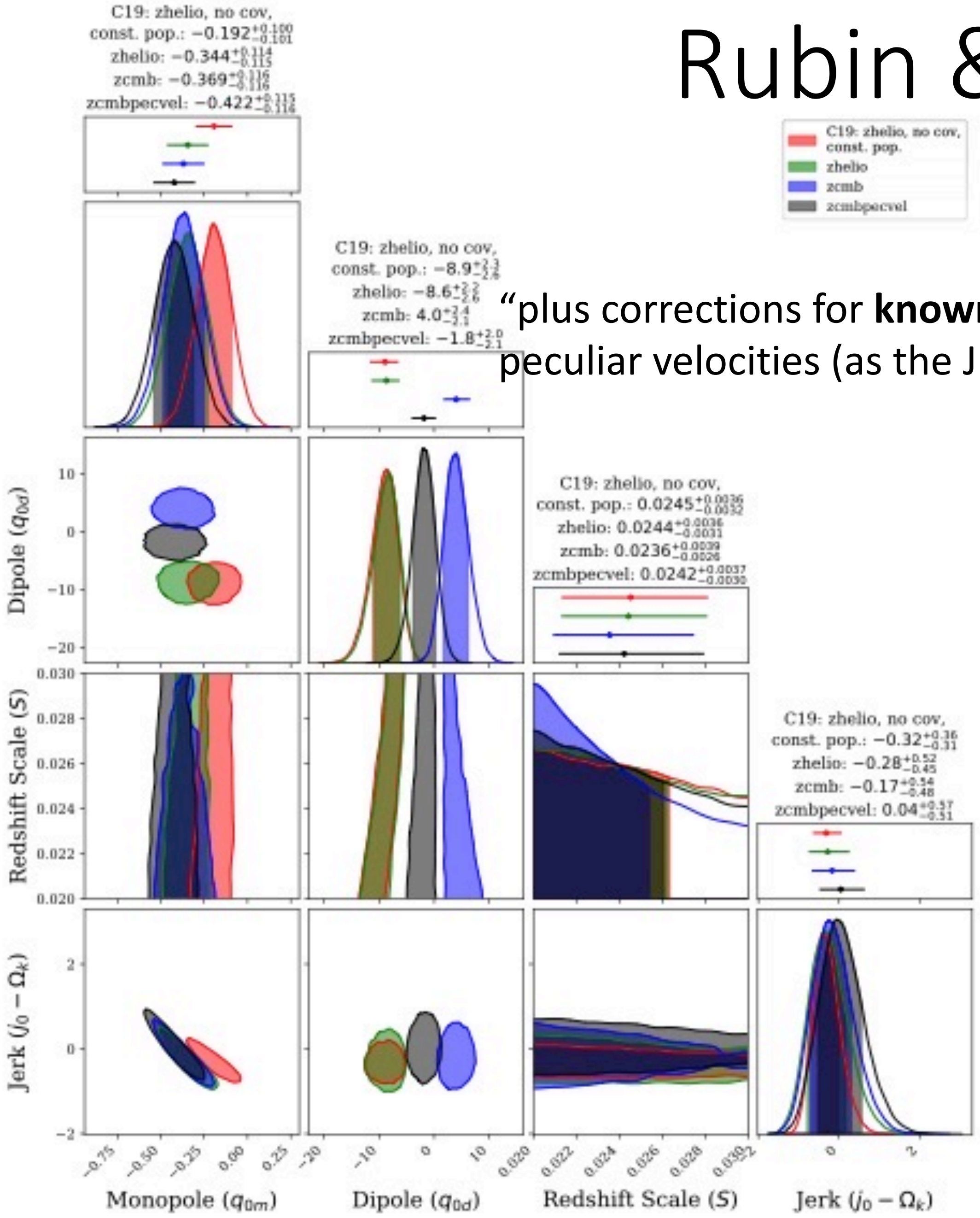
    An amusing debate: arXiv:1912.04257

The issue of peculiar velocities and corrections.

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

  A historical review of Supernova cosmology and fitting.

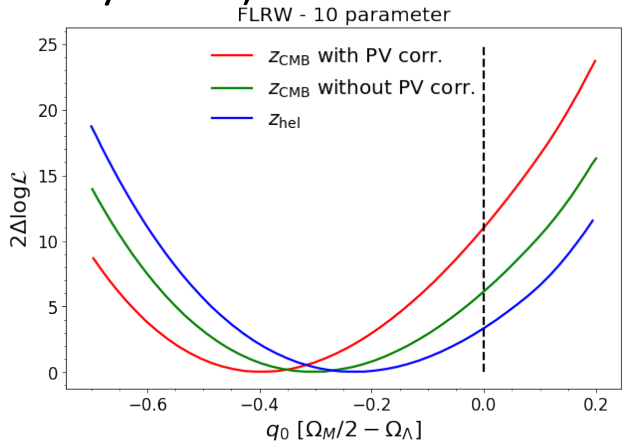
Rubin & Heitlauf 2019

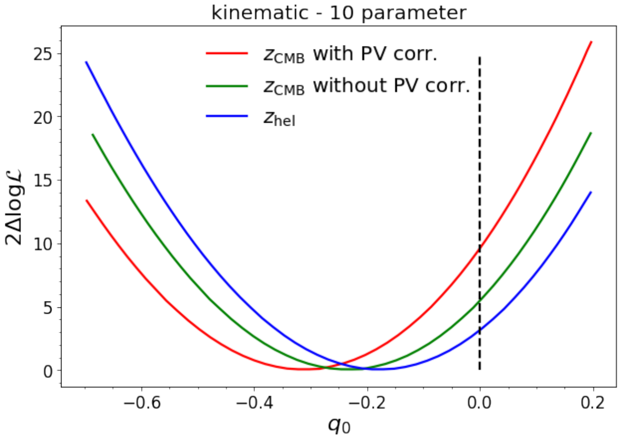


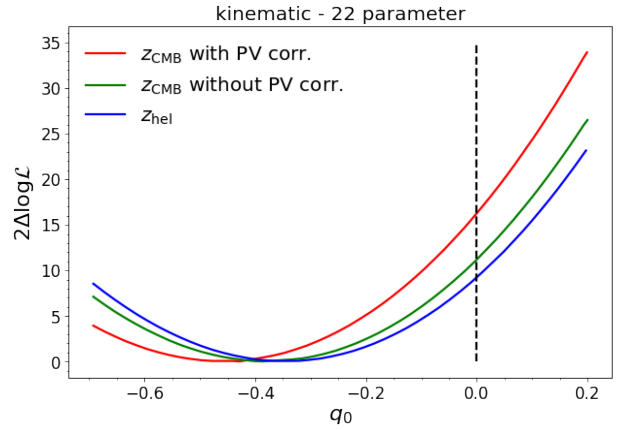
$$\Delta\mu_{pv} = \frac{5}{\log(10)}\frac{v}{zc}$$

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

Our Response







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

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

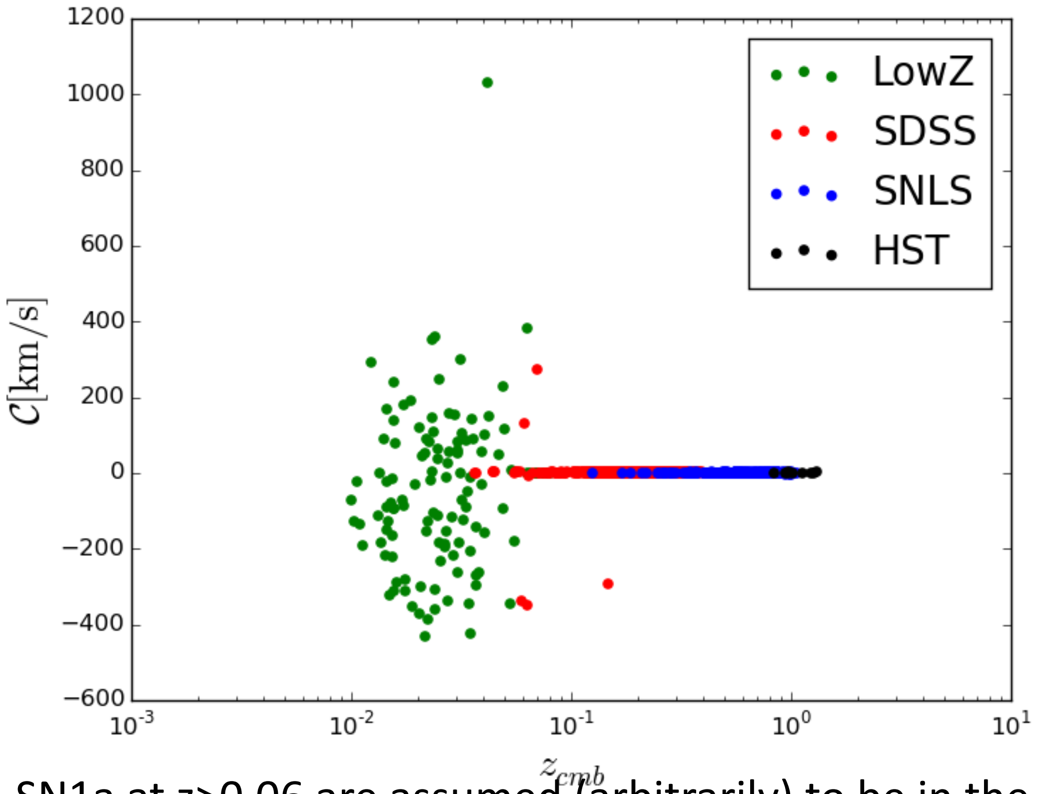
JLA (and Pantheon) redshifts and magnitudes have been ‘corrected’ to account for the local bulk flow.

#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				
03D1fq	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

Peculiar velocity impact on SN1a magnitude

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

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```
#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
```

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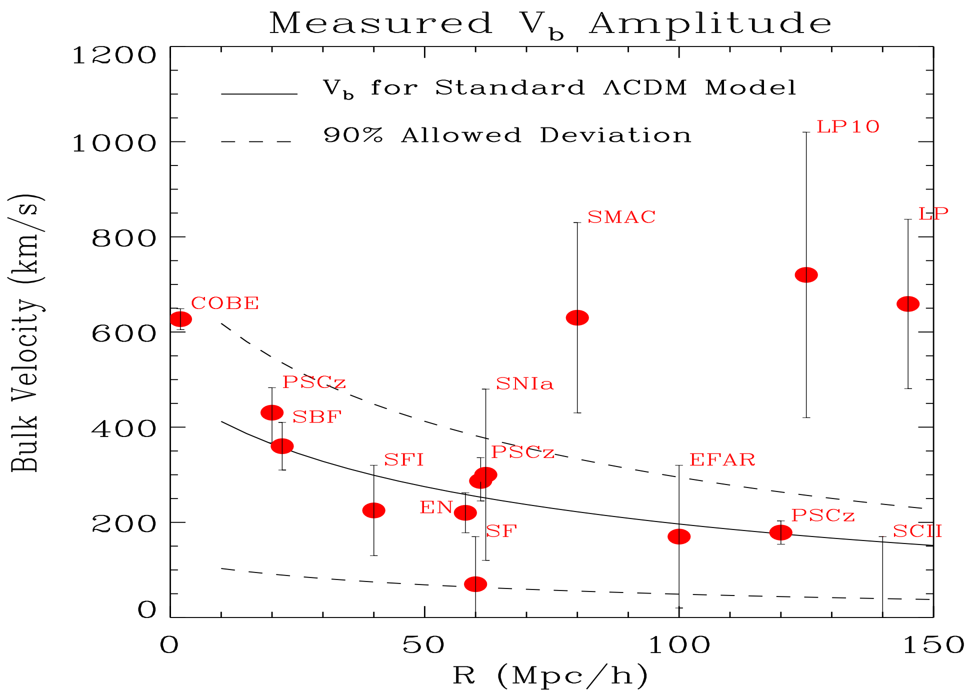
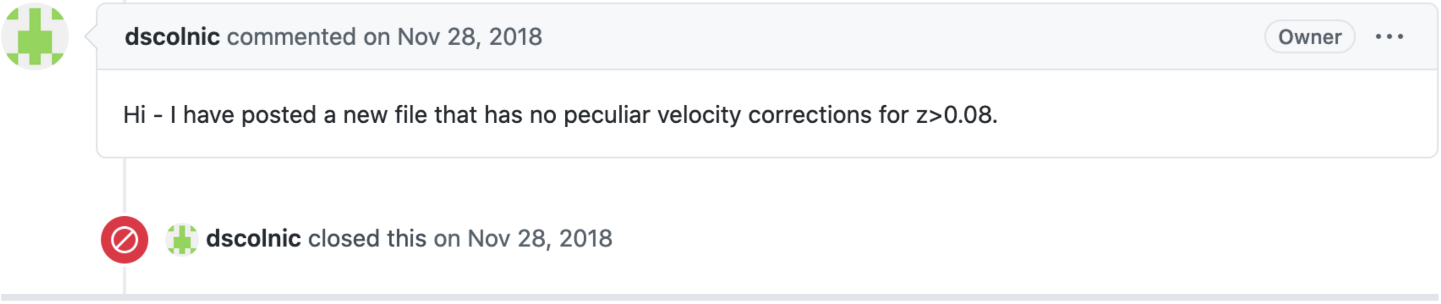


SN1a at z>0.06 are assumed (arbitrarily) to be in the CMB rest frame. (only uncorrelated 150 km/s in error budget)
Wrong ‘correction’ to SDSS2308 in JLA. Many such mistakes in Pantheon (eg : SN2246).
Flow model – SMAC has a ~600 km/s residual bulk flow

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

There is an arbitrary discontinuity within the data.

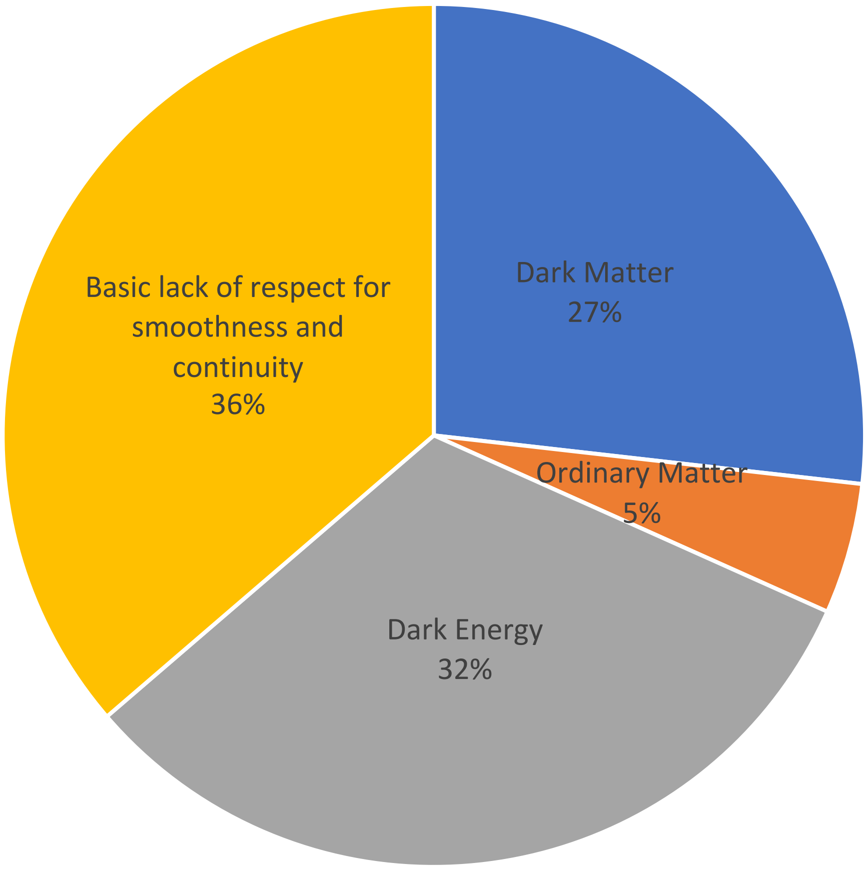
Also in the subsequent Pantheon compilation

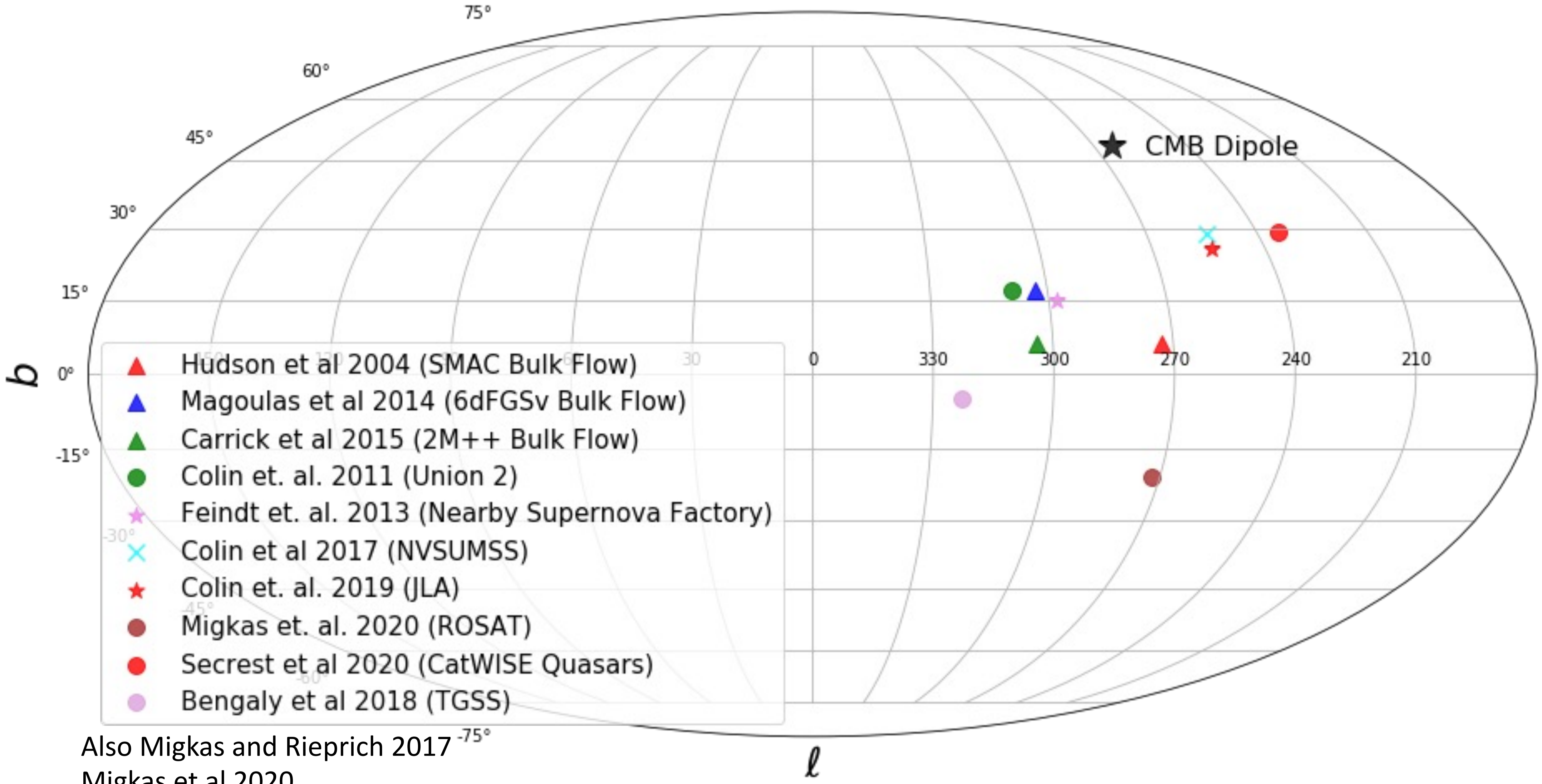


https://github.com/dscolnic/Pantheon/issues/2

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’

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

The FLRW universe

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

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

The cosmic sum rule

Maximal symmetry forbids peculiar velocities

The Real Universe

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

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

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

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

What we mean by ‘non Copernican observers’

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

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

Buchert and Heinesen 2020

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

Can be de
Friedman

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

hury Equation”
o. 1, July 2007

Maximal

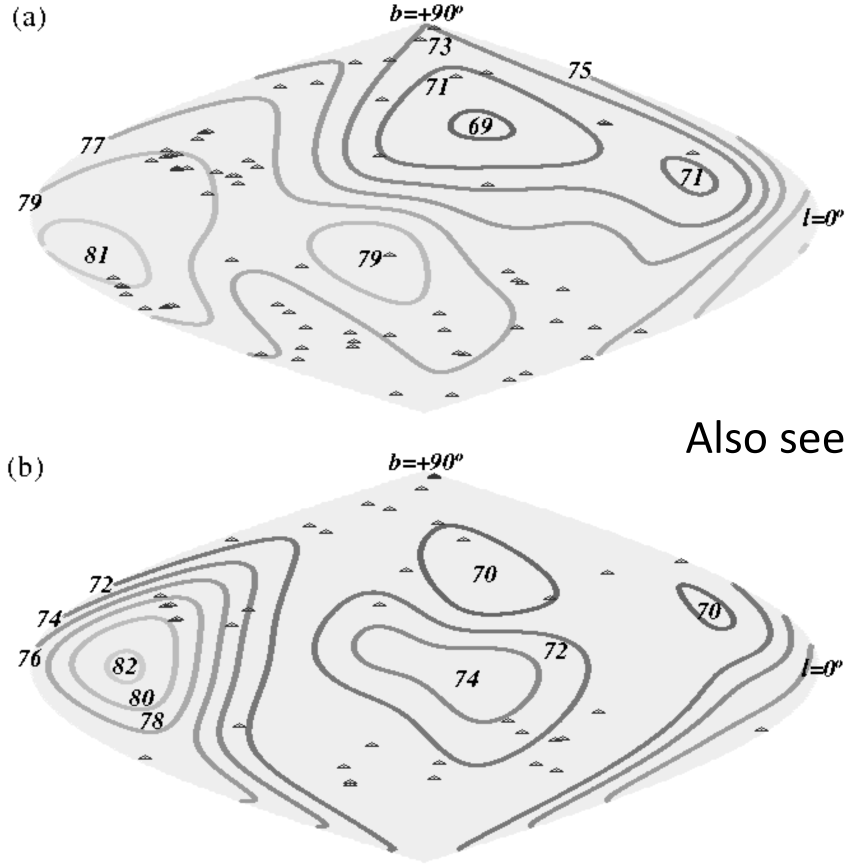
hould be
Jniverse

ms

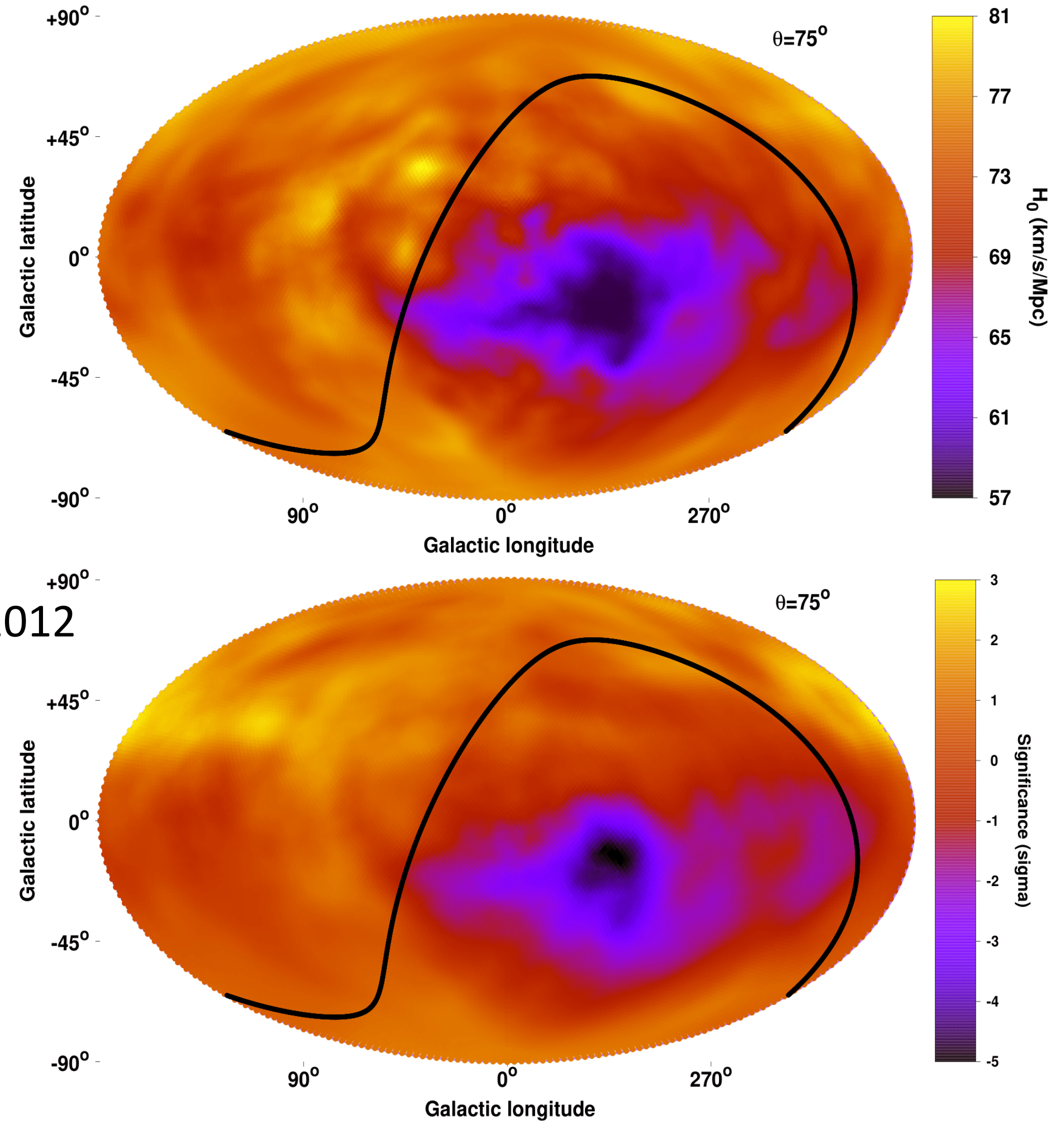
with which we do cosmology.

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

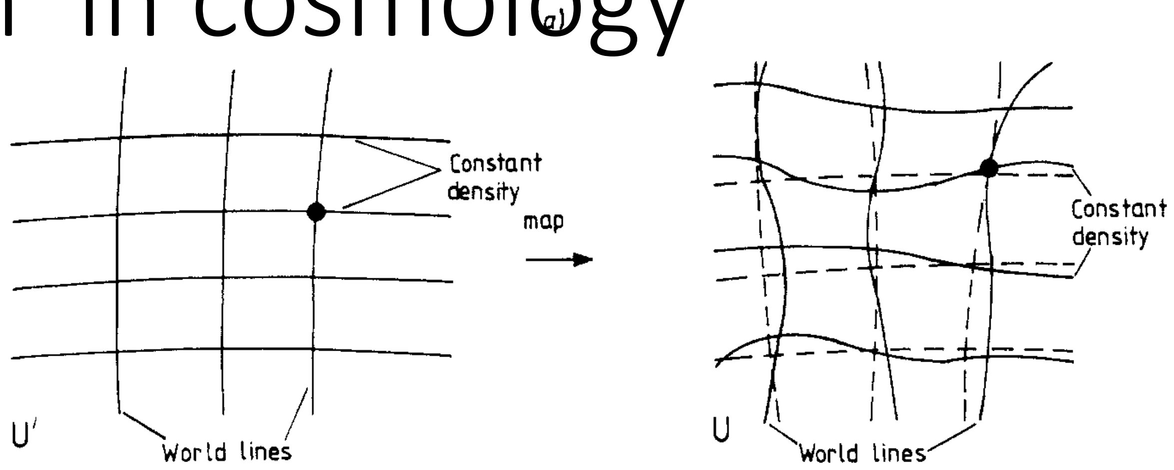
G F R Ellis† and W Stoeger‡

† School of Mathematics, Queen Mary College, Mile End Road, London E1 4NS, UK and Department of Applied Mathematics, University of Cape Town, Rondebosch 7700, South Africa
‡ Vatican Observatory, Castel Gandolfo, I-00120 Citta del Vaticano

Received 6 February 1987

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

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



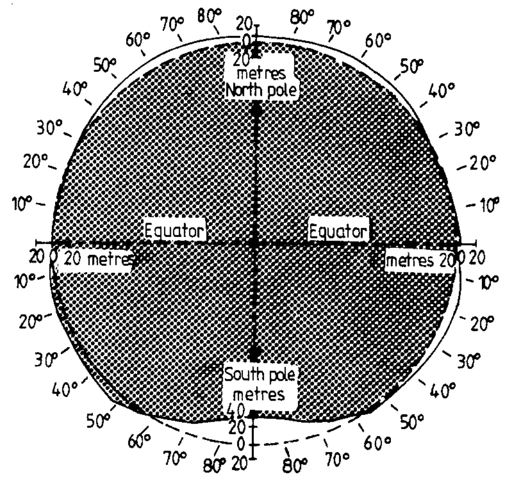


Figure 1. (*a*) An exactly uniform and spherically symmetrical FLRW universe U′ mapped into the lumpy universe U so as to give the best fit possible. (*b*) An exactly spherical sphere fitted to the lumpy world to give the best fit possible.

Results

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

	$-2\log\mathcal{L}_{\max}$	$q_{\rm m}$	$q_{\rm d}$	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 ($q_{\rm d}=0$)	−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. ($q_{\rm m}=0$)	−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.

	$-2\log\mathcal{L}_{\max}$	$q_{\rm m}$	$q_{\rm d}$	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 ($q_{\rm d}=0$)	−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. ($q_{\rm m}=0$)	−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’!

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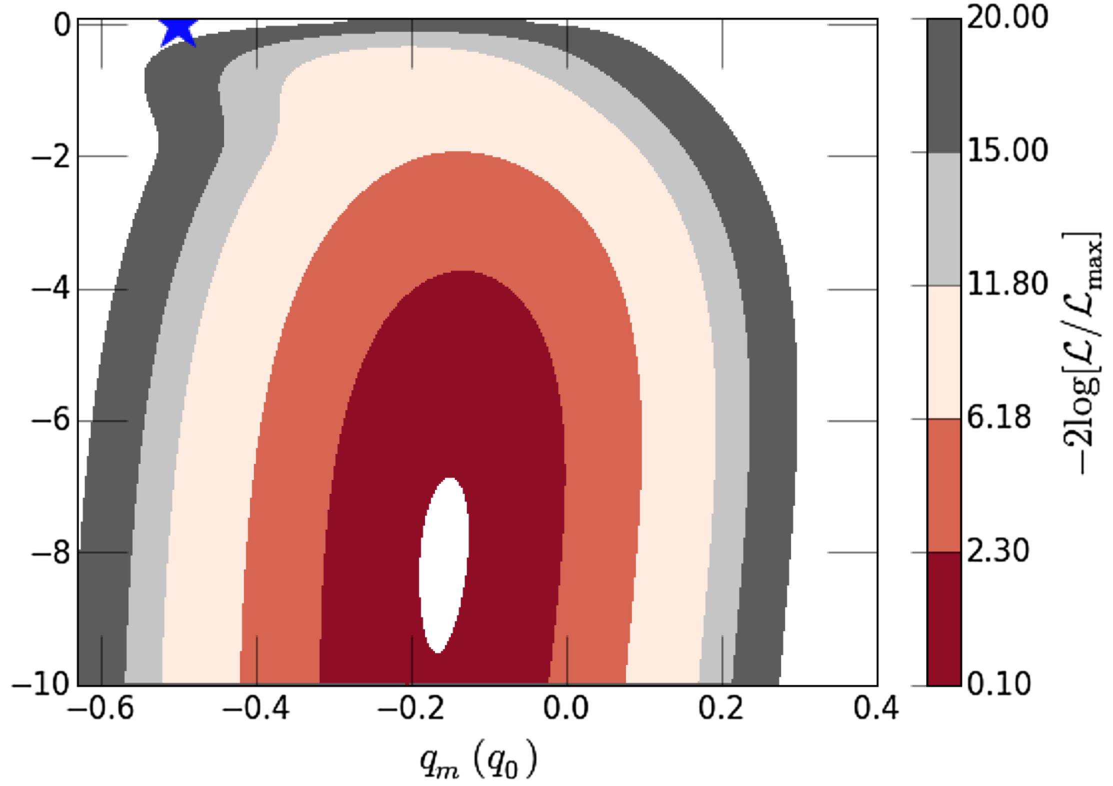

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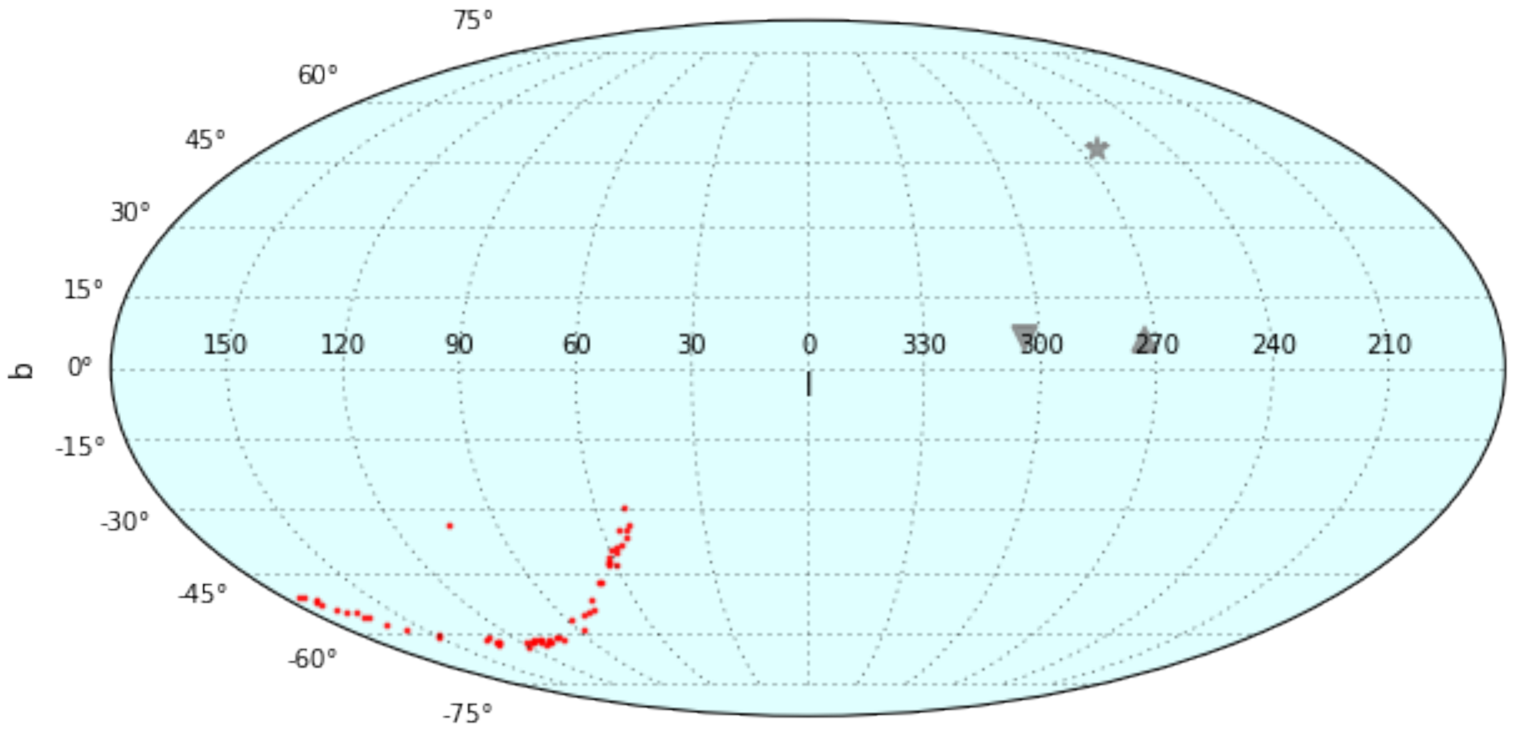
1905.00221 : The only ‘dark energy’ I found in cosmology



JLA (740) -> Pantheon (1080)
The redshifts of ~150 SNe changed, 58 at > 5 sigma level, some at 137 sigma
$z_{diff} \sim 0.1$ for some

General covariance.

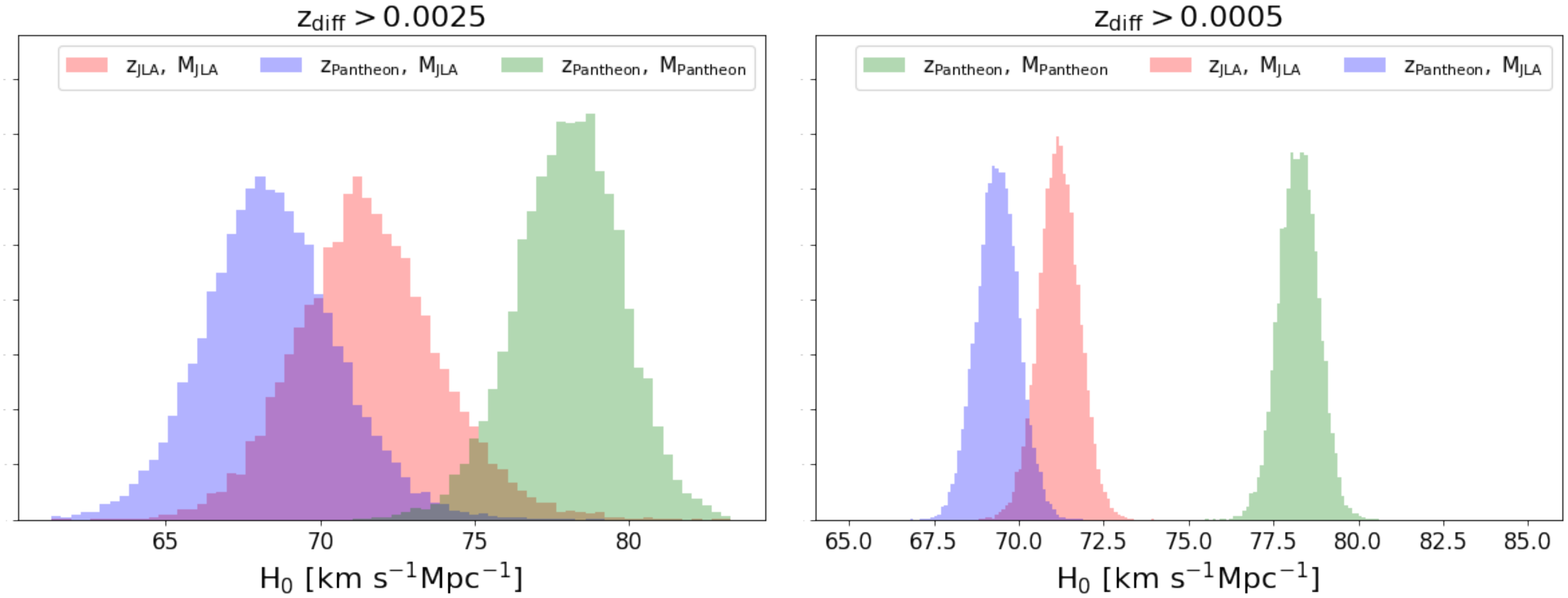
‘high redshift supernovae were found to be dimmer (15% in flux) than the low redshift supernovae (compared to what would be expected in a   universe)’ (Perlmutter et al 1999)

Peculiar velocity ‘corrections’:

1. Change the redshifts and magnitudes of low z Sne by up to 20%
2. Introduce arbitrary discontinuities within intrinsically scattered data
3. Peculiar velocity ‘corrections’ first stretched all the way to z~0.3 (where there is no peculiar velocity information)

Even observed quantities are changing

A trivial solution to the Hubble tension? 1911.06456



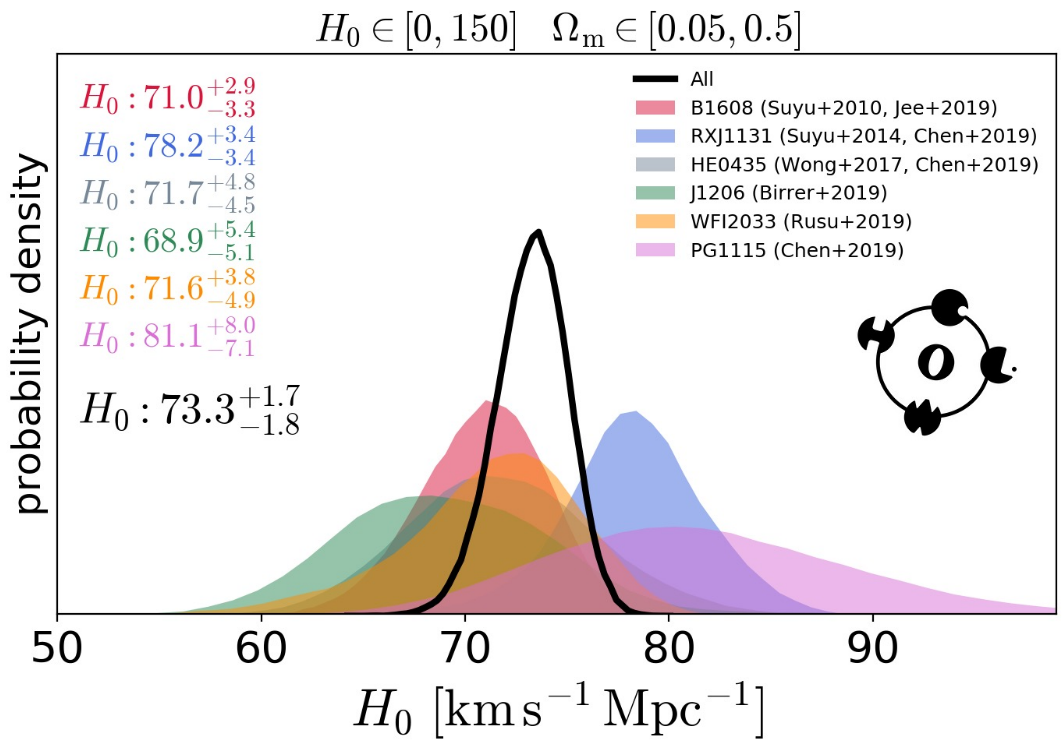
The shifts in redshift and magnitude appear to be sufficient to lower the Hubble ‘constant’ from ~72 to 68, keeping many other parameters fixed to that of Riess et al 2016

What is ΛCDM cosmology?

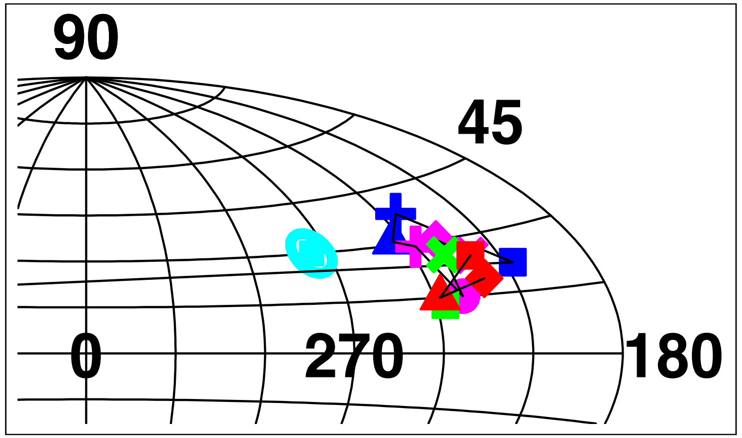
The naive fitting of data from the real Lumpy Universe, to a smooth toy model, treating all scatter as statistical, when it could be cosmological

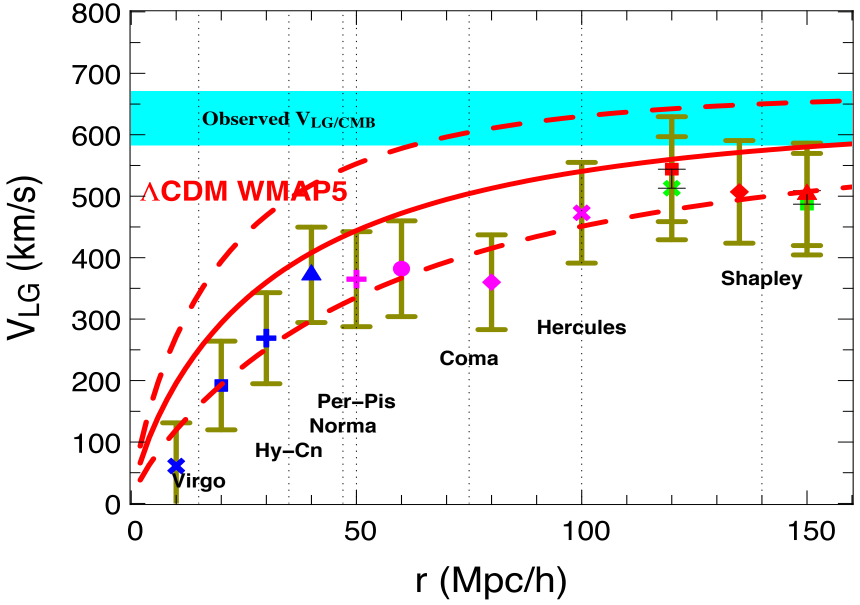
Such as this H0licow measuement

Note : This is very honestly communicated



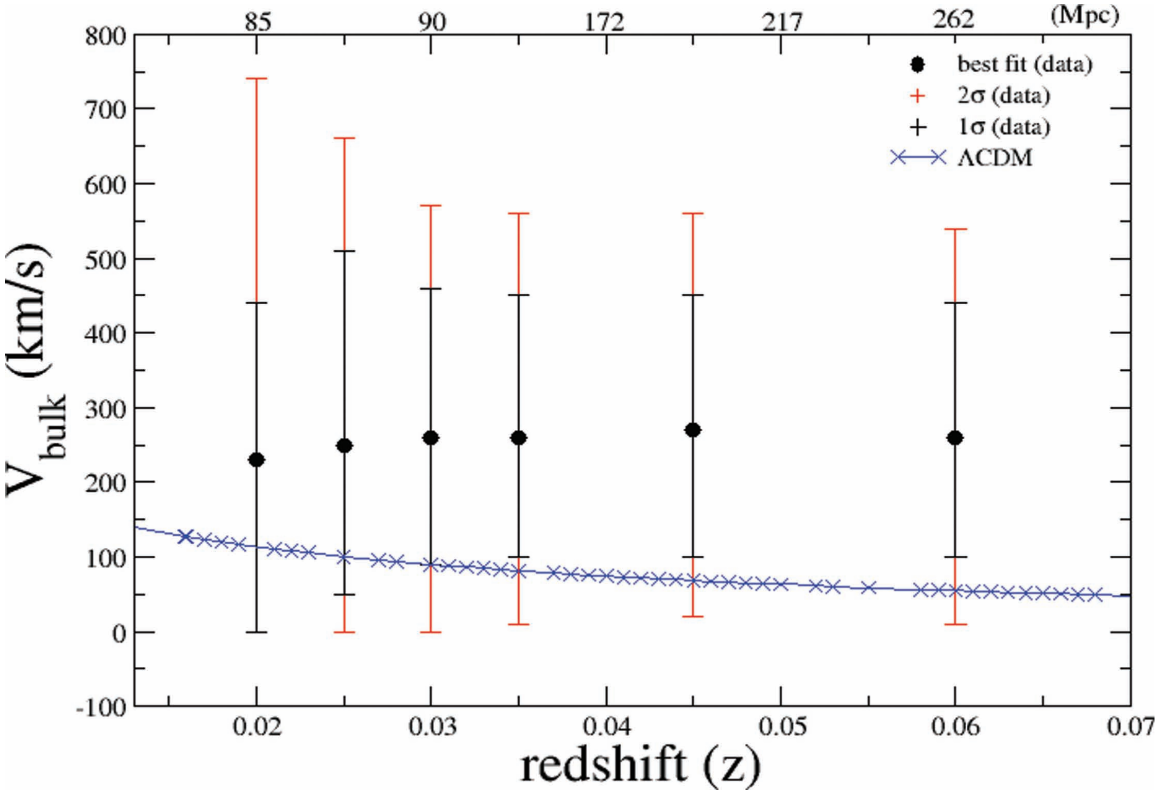
Where is the cosmic 'rest frame'?





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

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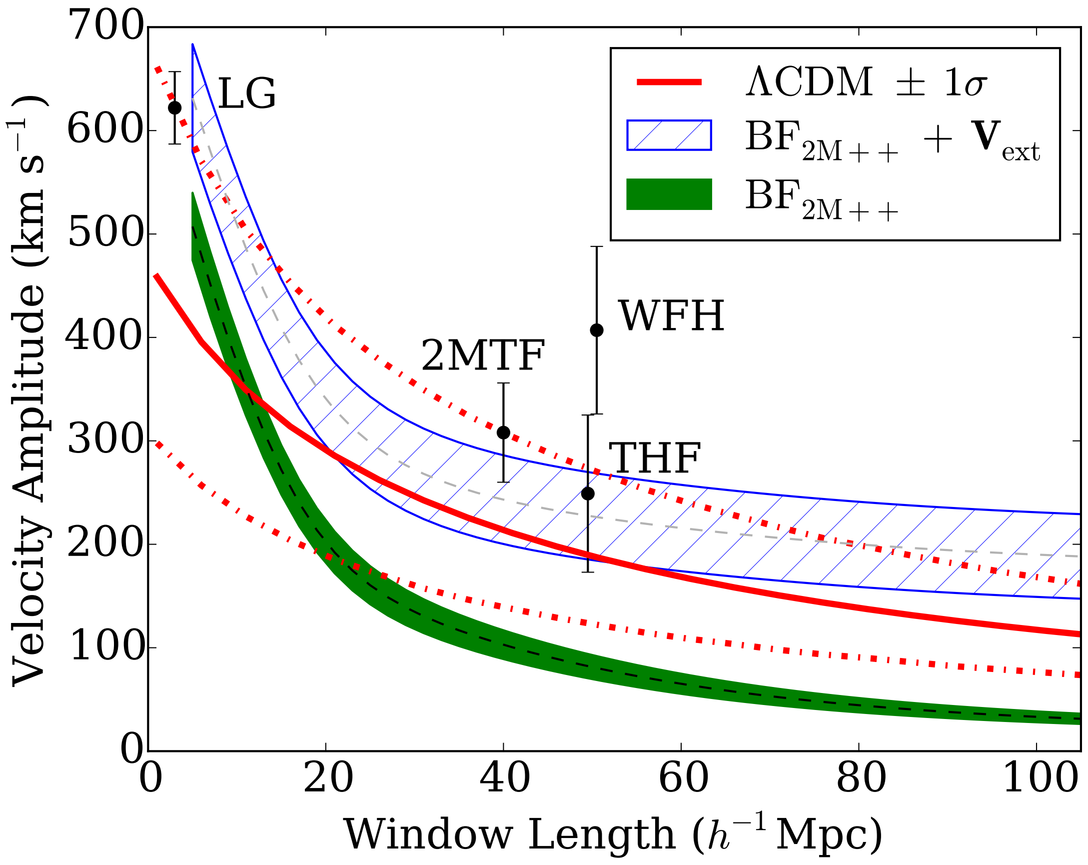

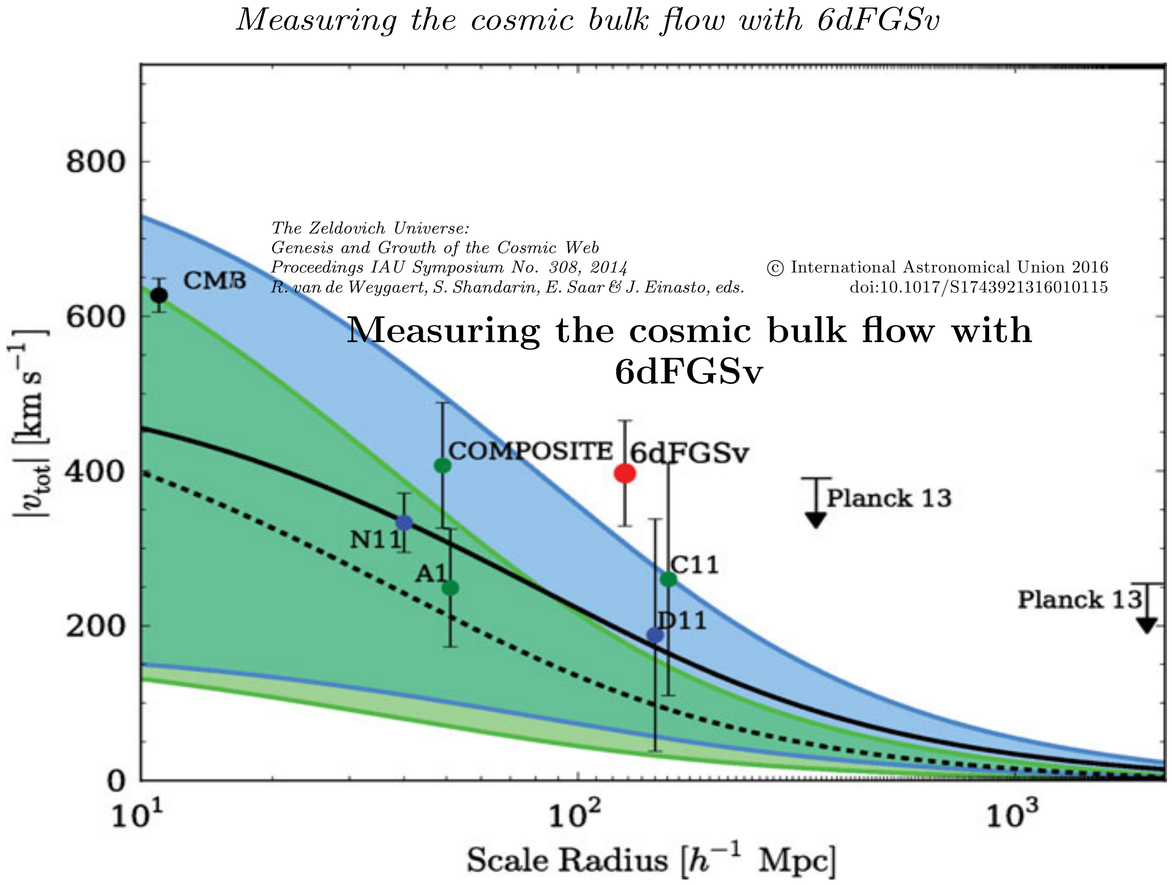

Carrick, Turnbull, Lavaux, Hudson *MNRAS*, 450, 1, 11 2015, 317–332

"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

G F R Ellis† and W Stoeger‡

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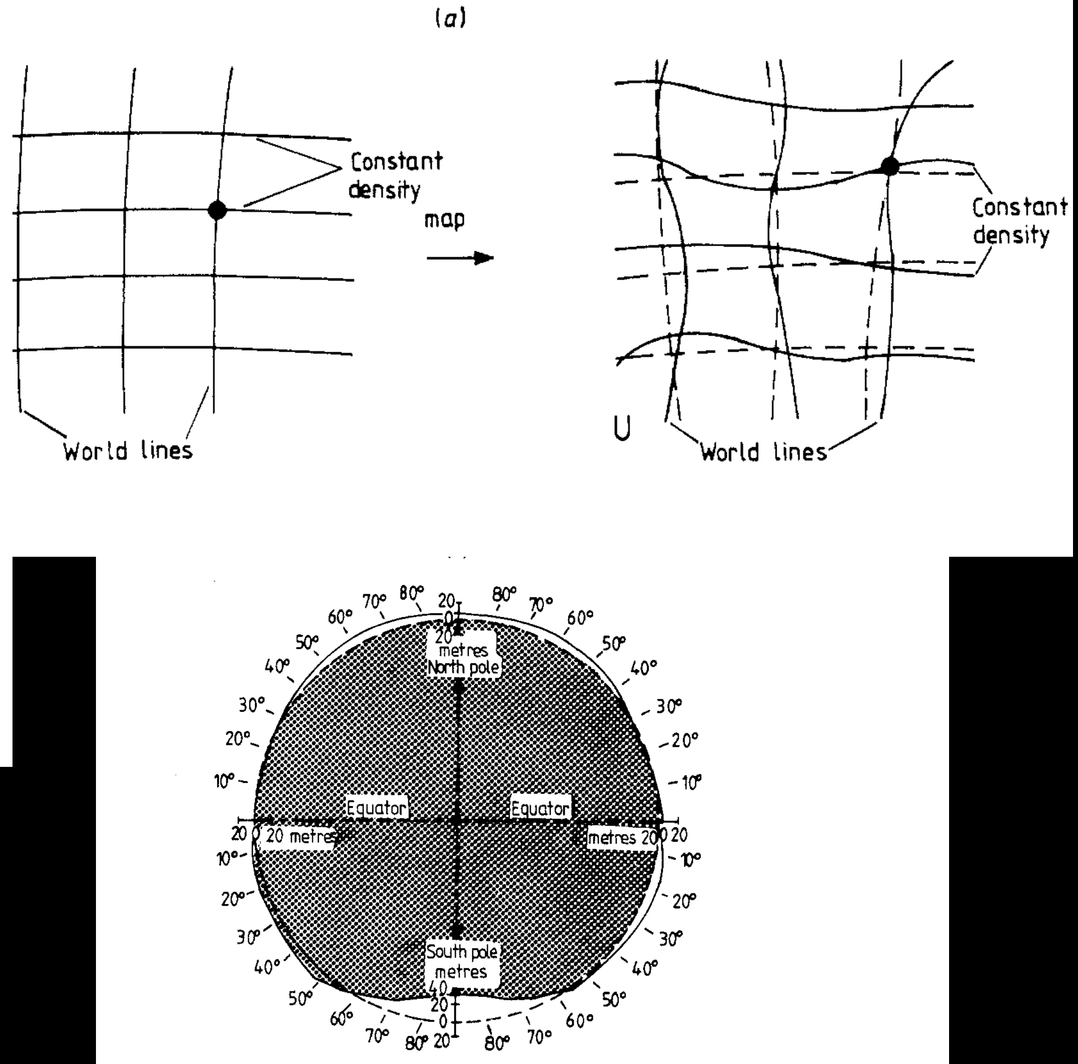

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Section 4.3 and 4.4 give a detailed discussion of how to correct for peculiar velocities, isotropize data, fit it to an idealized model, judge goodness of fit and what it means for fundamental physics

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.

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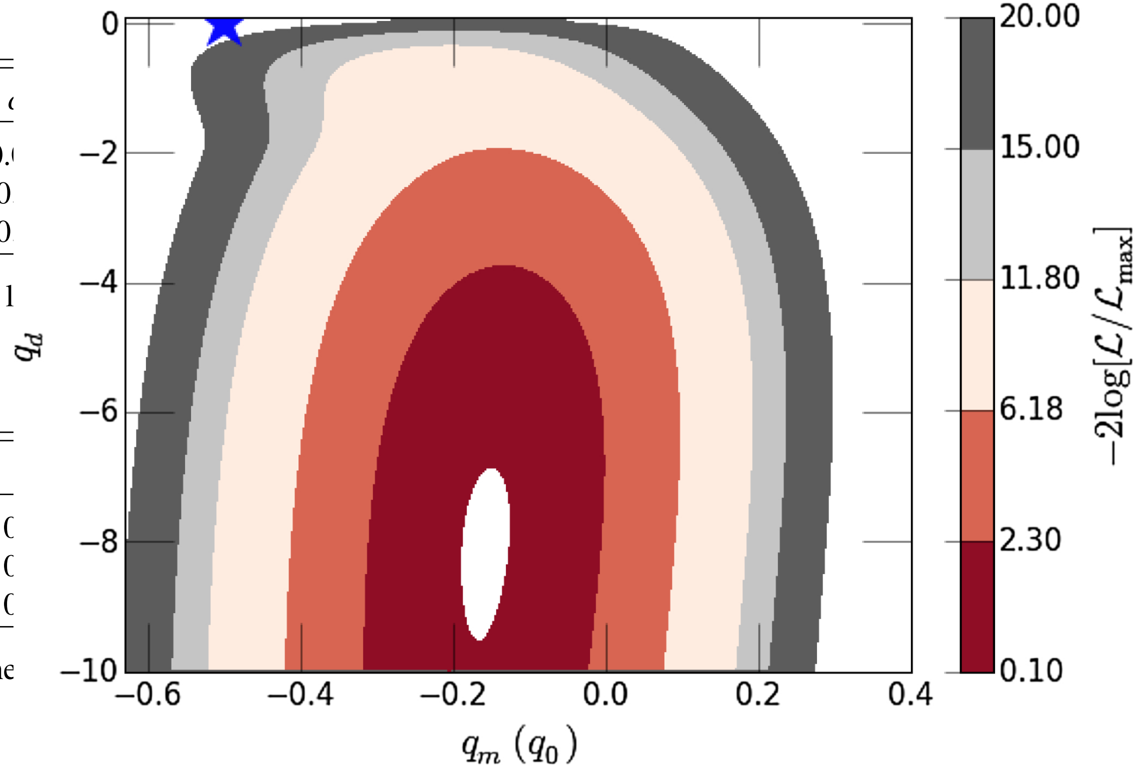

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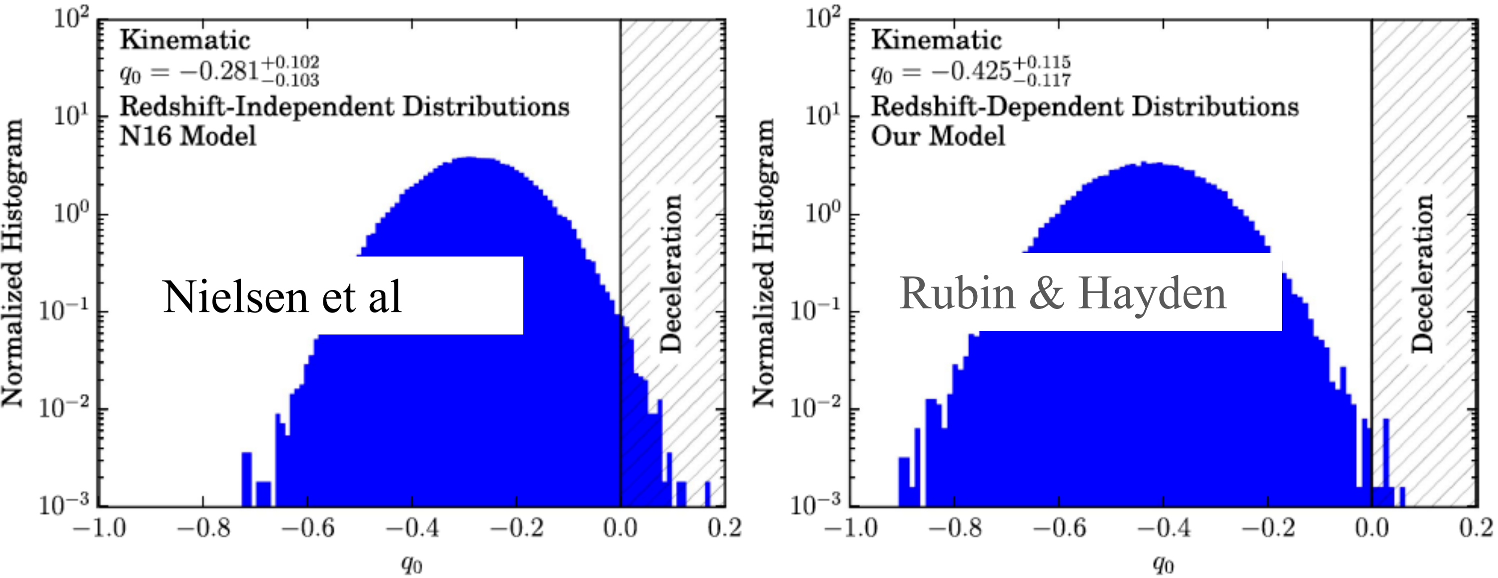
$q_d >> q_m$

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



Deceleration parameter

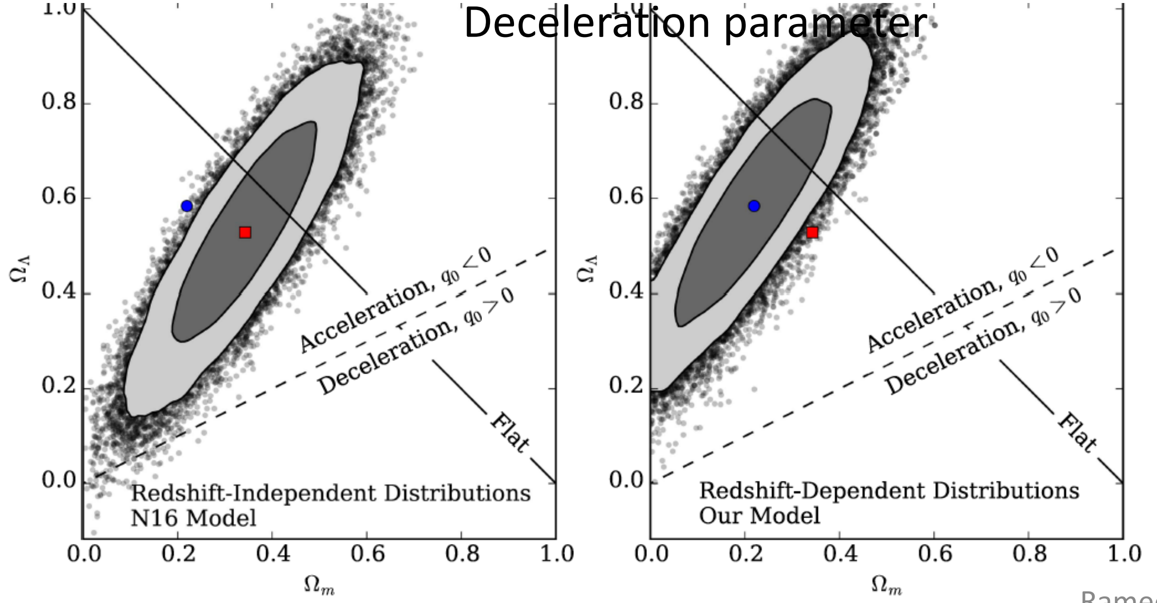


Figure 2. Ω_m–Ω_Λ constraints enclosing 68.3% and 95.4% of the samples from the posterior. Underneath, we plot all samples. The left panel shows the constraints obtained with x_1 and c distributions that are constant in redshift, as in the N16 analysis; the right panel shows the constraints from our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

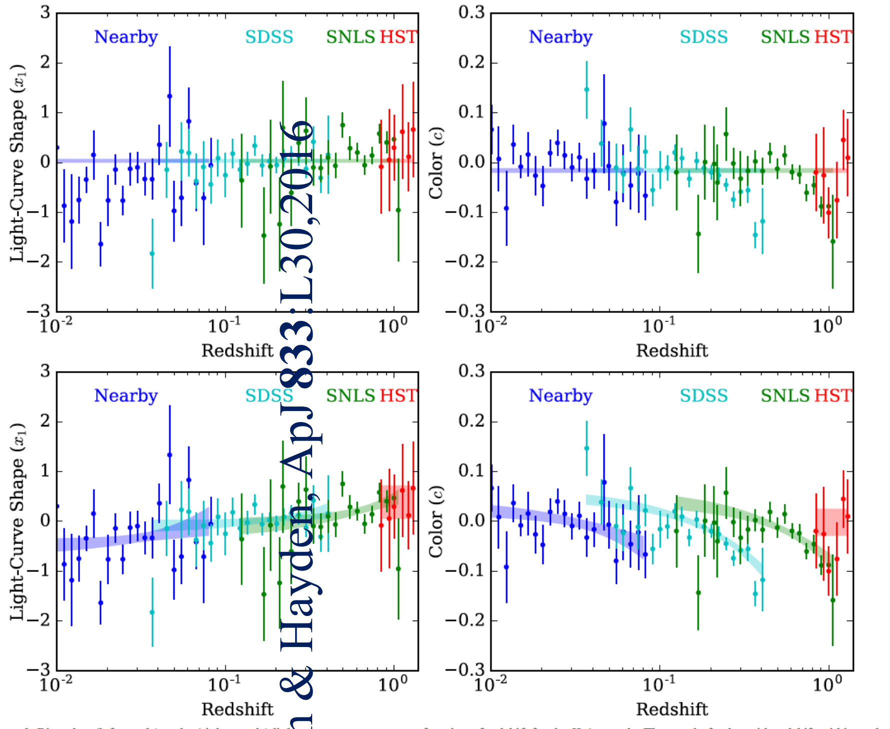


Figure 1. Binned x_1 (left panels) and c (right panels) light-curve parameters as a function of redshift for the JLA sample. The trend of color with redshift within each ground-based sample is expected due to the combination of the color-luminosity relation combined with redshift-dependent luminosity 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.

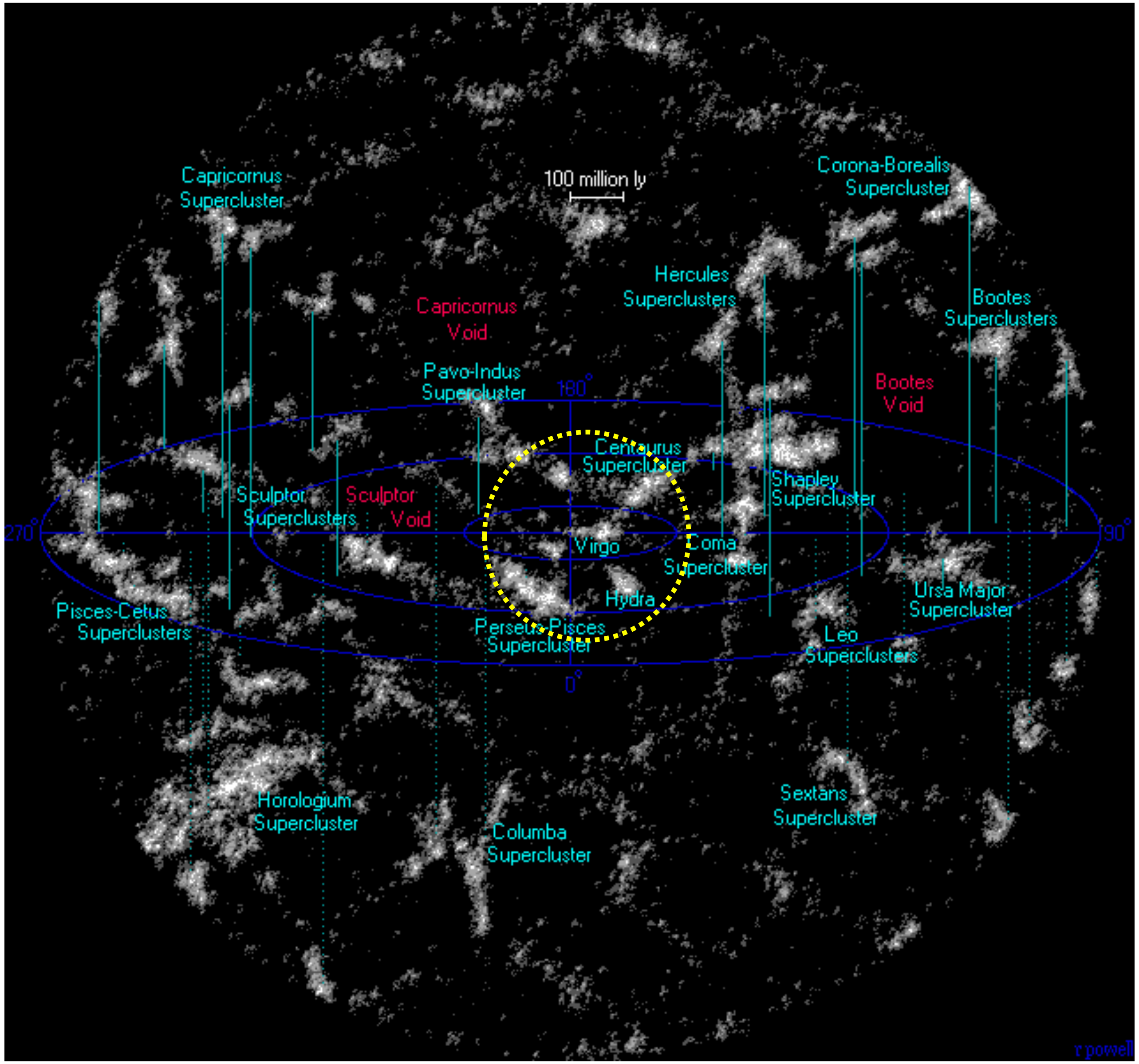
Rubin & Hayden, ApJ 833:L30,2016

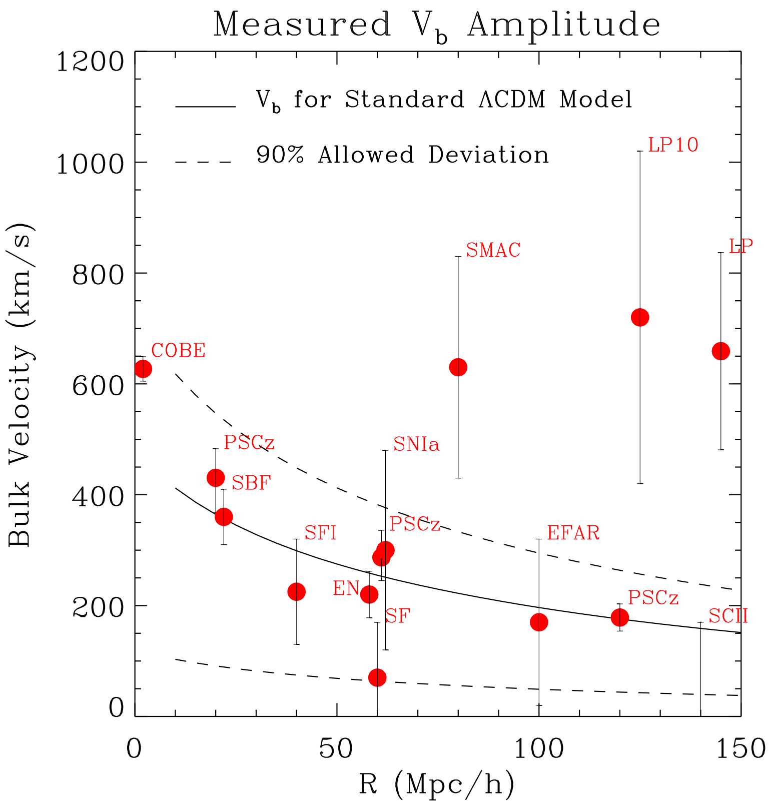
Two out of 3 parameters that go into the distance modulus have been examined by eye and made sample and redshift dependent.

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)!

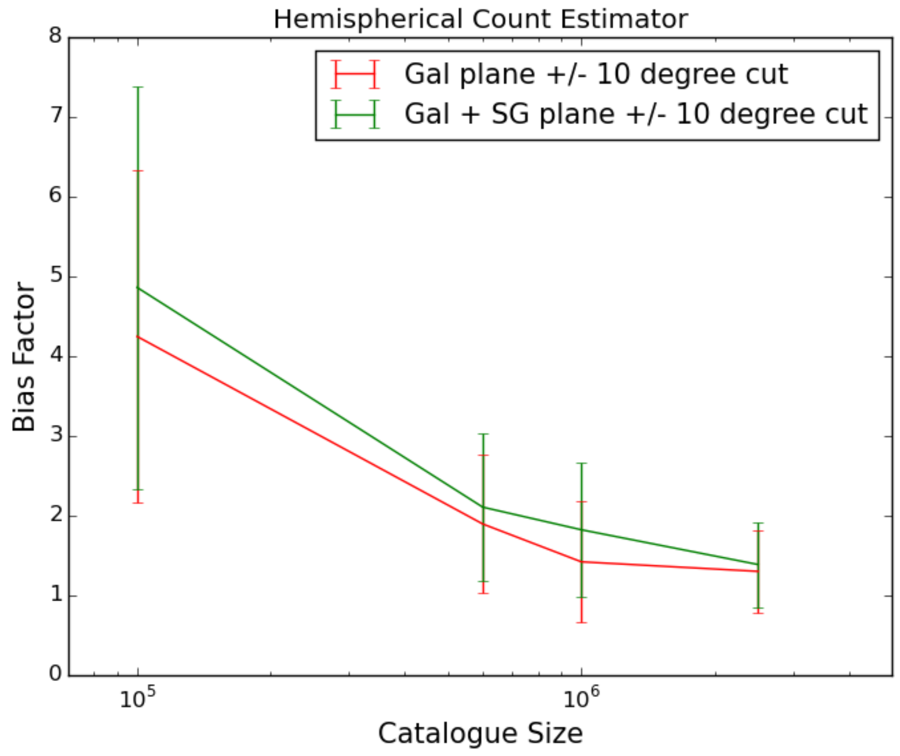

Capricornus Supercluster
100 million ly
Corona-Borealis Supercluster
Hercules Superclusters
Capricornus Void
Bootes Superclusters
Pavo-Indus Supercluster
180°
Bootes Void
Centaurus Supercluster
Shapley Supercluster
Sculptor Superclusters
Sculptor Void
270°
90°
Virgo
Coma Supercluster
Hydra
Ursa Major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

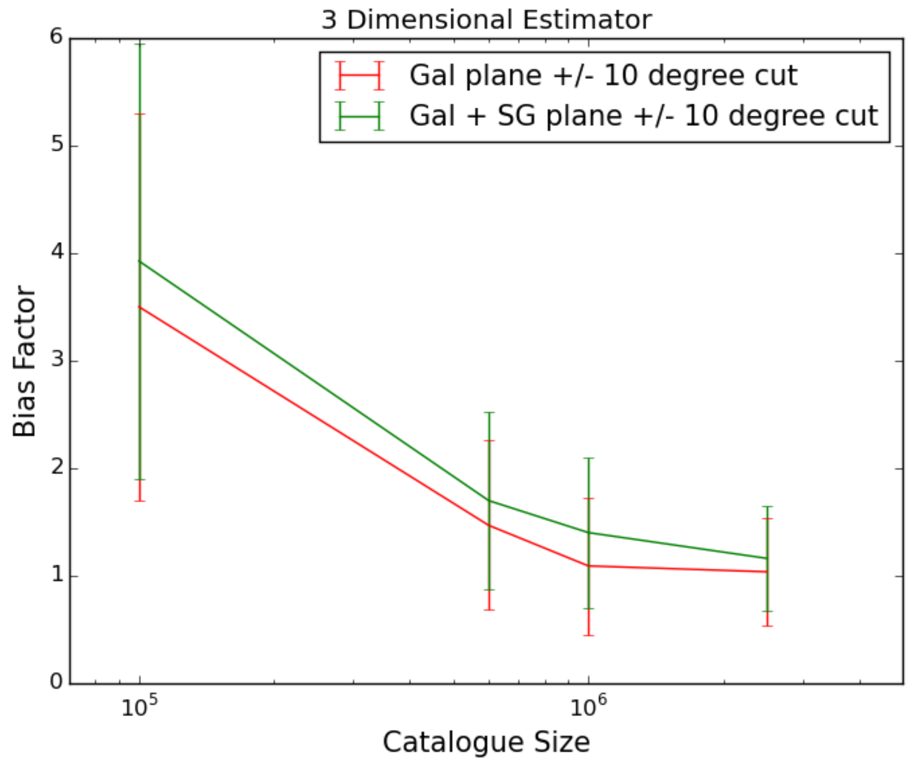

Measured V_b Amplitude
V_b for Standard ΛCDM Model
90% Allowed Deviation
Bulk Velocity (km/s)
R (Mpc/h)
0
200
400
600
800
1000
1200
50
100
150
COBE
PSCz
SBF
SFI
EN
SF
SNIa
PSCz
SMAC
EFAR
PSCz
SCII
LP10
LP

Estimators for the Dipole

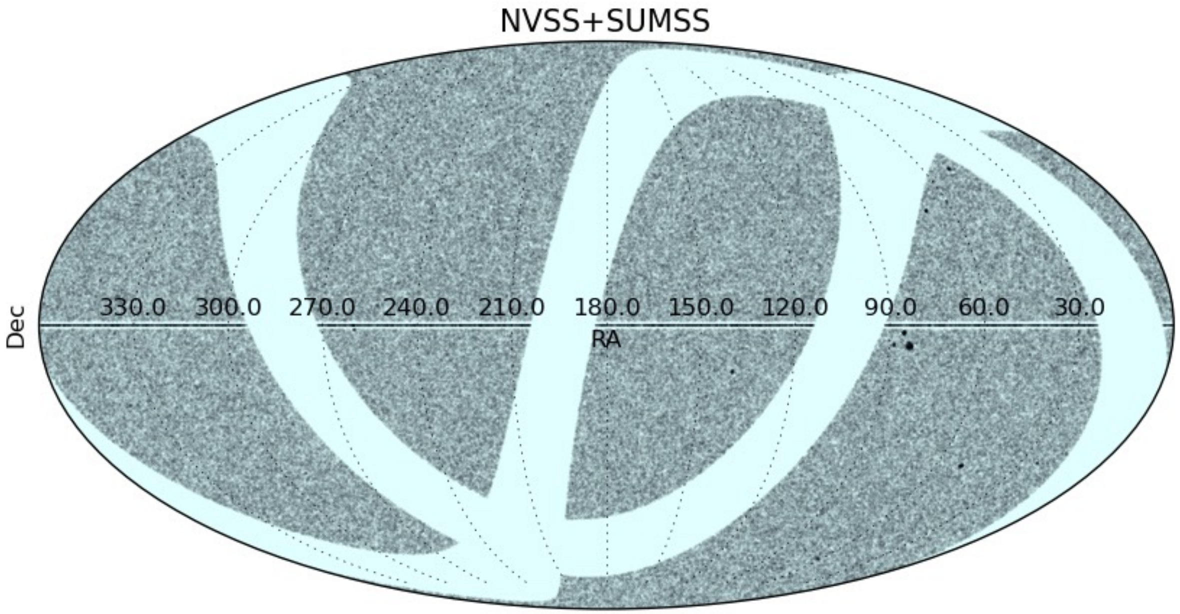
$$\vec{D}_H = \hat{z} * \frac{N_{UH} - N_{LH}}{N_{UH} + N_{LH}}$$

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





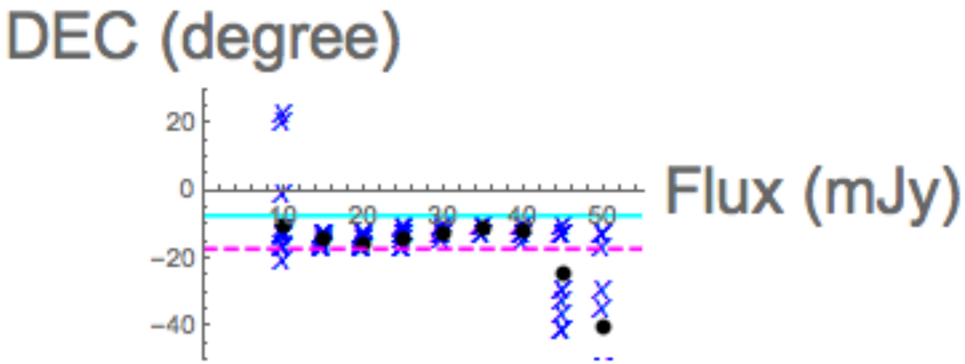
Local Sources contamination?

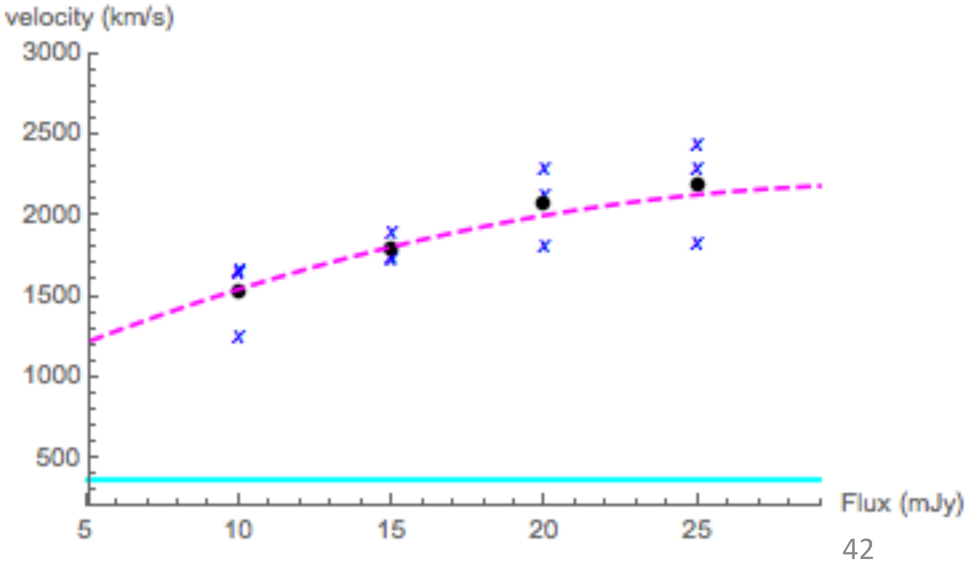


Remove the Supergalactic plane. Disk like structure containing the majority of clusters at z<0.03

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

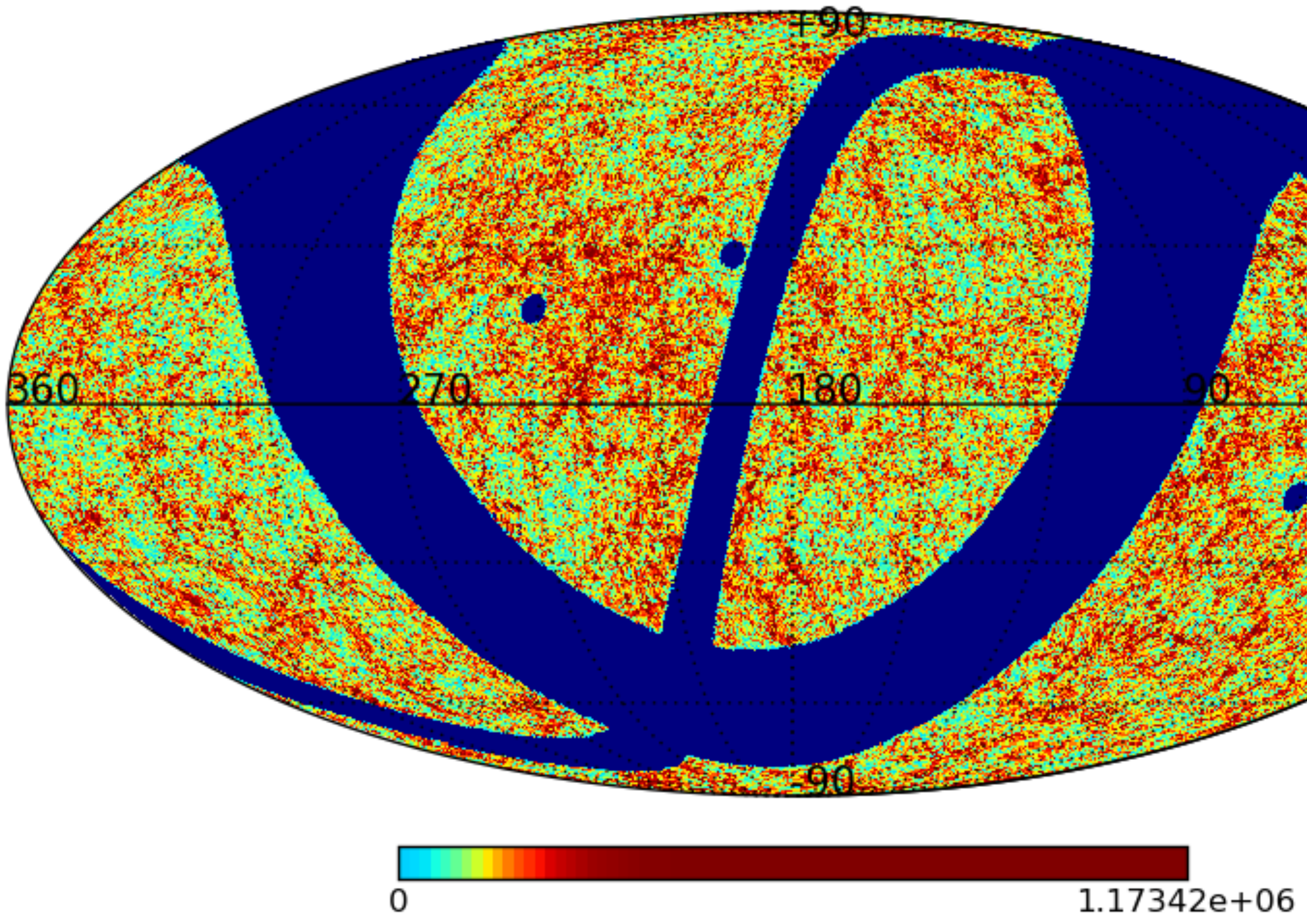
https://arxiv.org/pdf/1505.07800.pdf

On the measurement of cosmological parameters

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

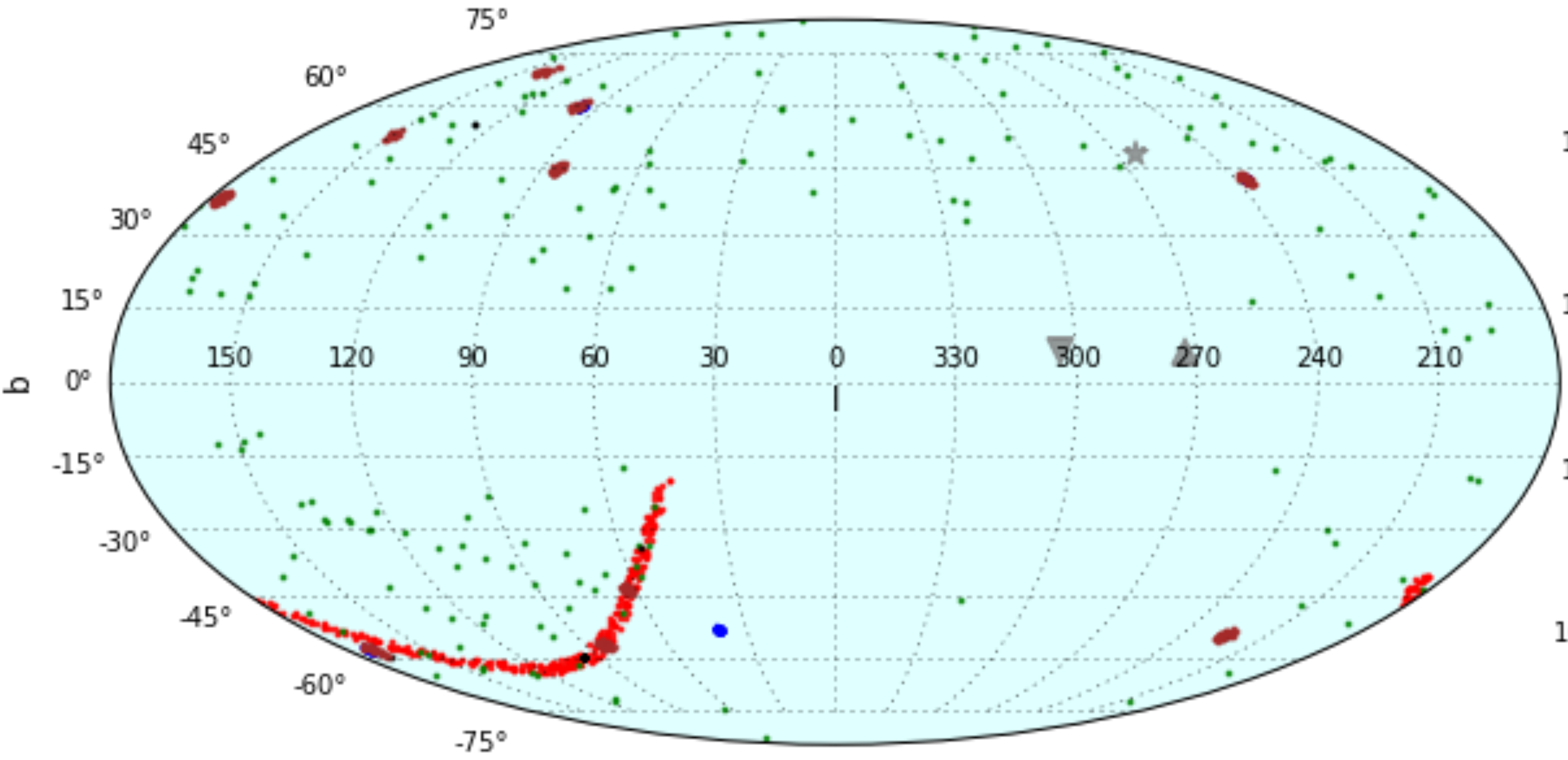
(Submitted on 14 Dec 2011 (v1), last revised 21 Jul 2015 (this version, v2))

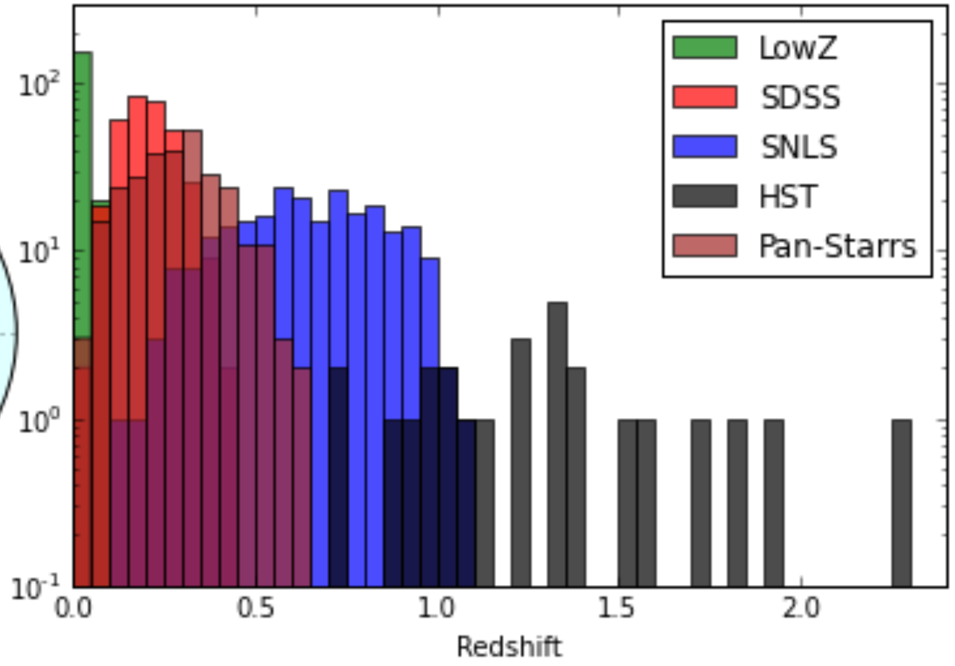
We have catalogued and analysed cosmological parameter determinations and their error bars published between the years 1990 and 2010. Our study focuses on the number of measurements, their precision and their accuracy. The accuracy of past measurements is gauged by comparison with the WMAP7 results. 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 fluctutations 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

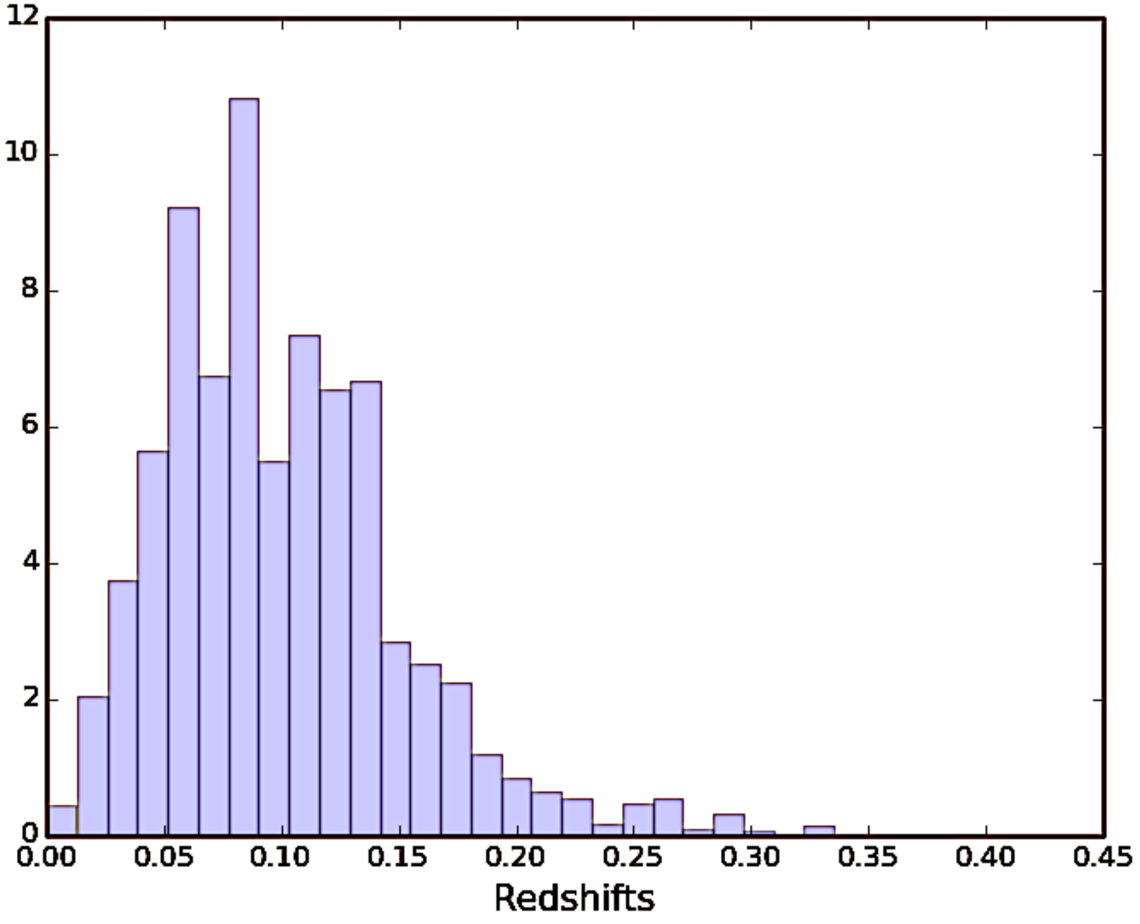




JLA + additional SN1a from Pan Starrs and HST
1048 SN1a, redshifts corrected for peculiar velocities using the 2M++ flow field
890 are in the hemisphere opposite the 2M++ bulk flow

However, we use only JLA!

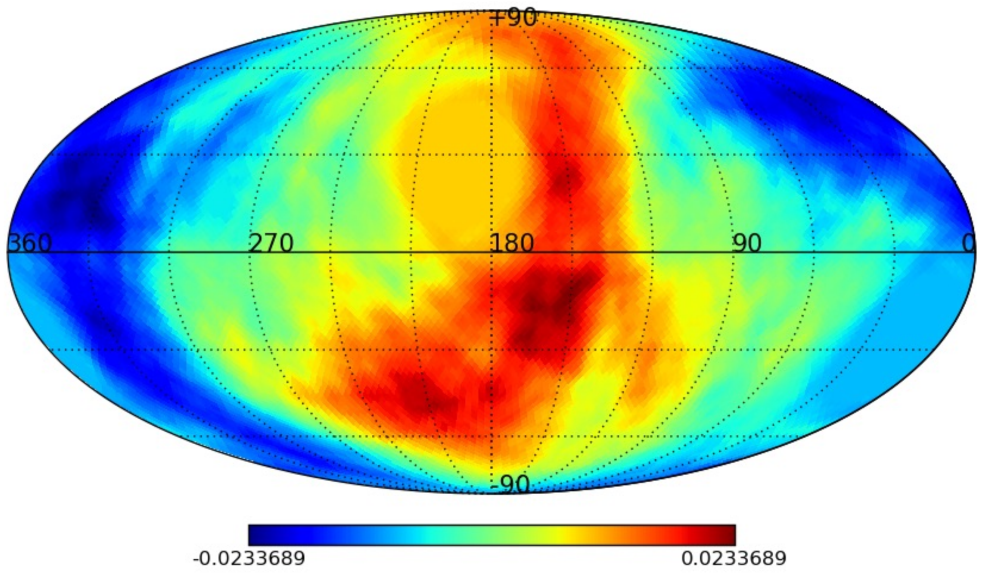
Redshift distribution of the removed sources



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)

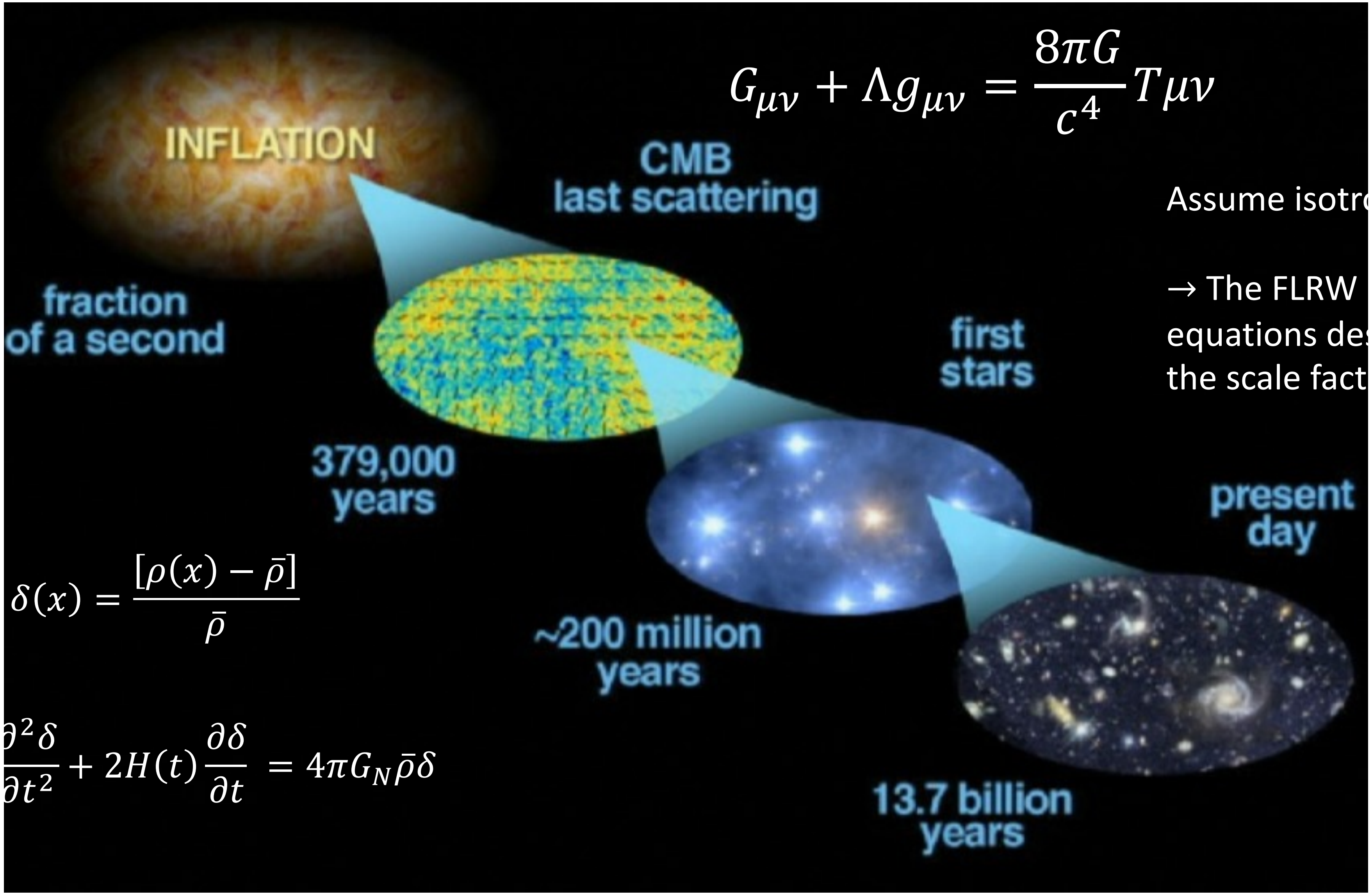
Total dipole is at least 4.2σ statistically significant.



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

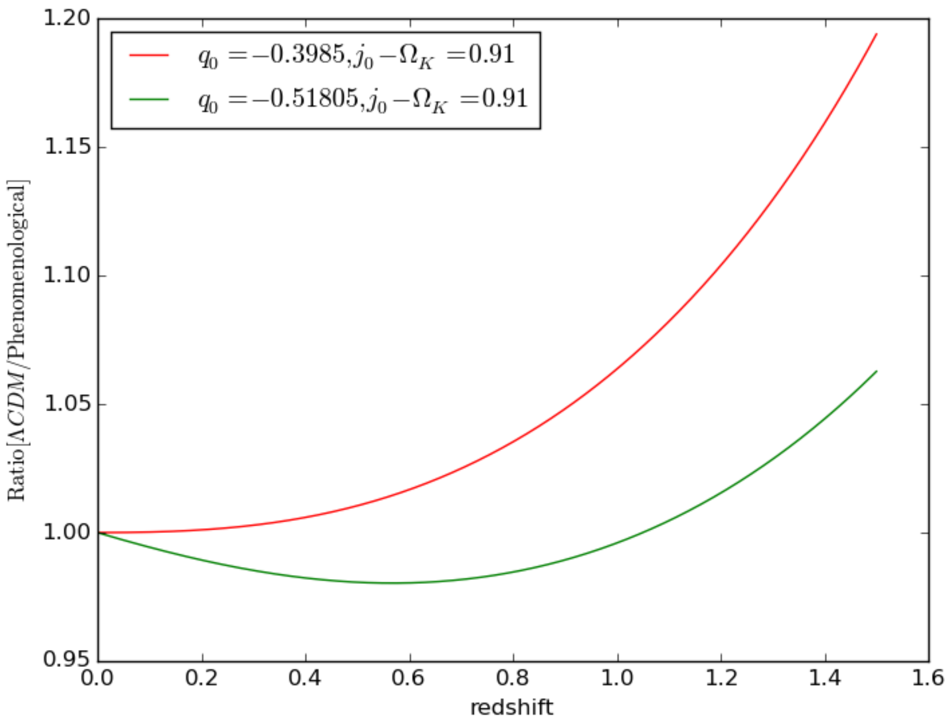
Assume isotr

→ The FLRW
equations des
the scale fact

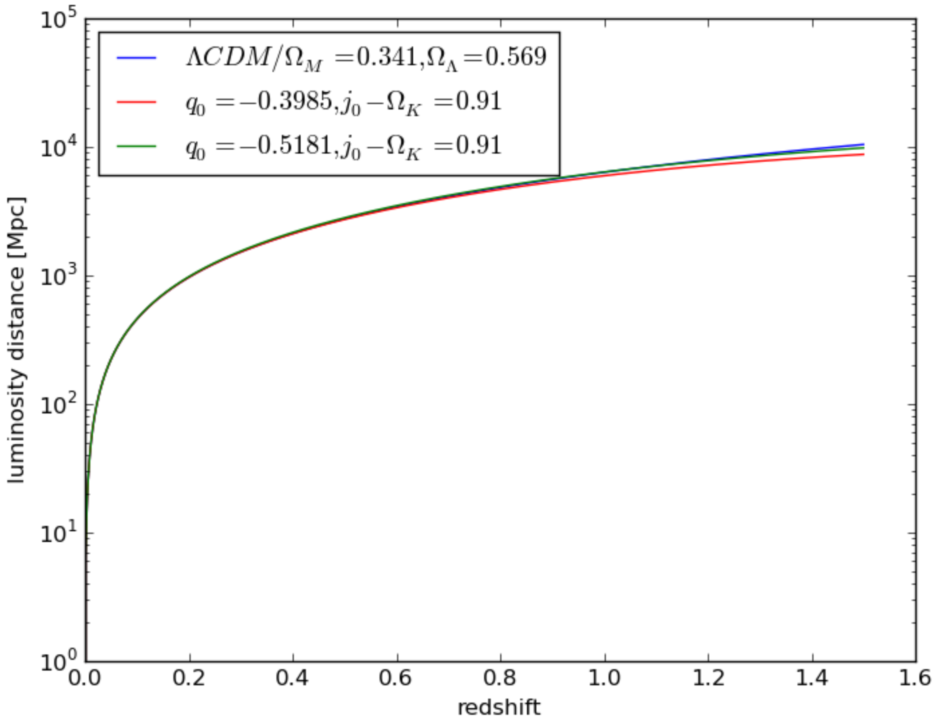


$$\delta(x) = \frac{[\rho(x) - \bar{\rho}]}{\bar{\rho}}$$

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



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]
$\Lambda CDM/\Omega_M = 0.341, \Omega_\Lambda = 0.569$
$q_0 = -0.3985, j_0 - \Omega_K = 0.91$
$q_0 = -0.5181, j_0 - \Omega_K = 0.91$

The FLRW Universe

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

Cosmological Backreaction

At the very least, then, these considerations surely tell us that it is important to understand the averaging, fitting and backreaction problems to see what effects there may be on cosmology. There are some scales where backreaction may be important - probably not the largest scales relevant to the cosmic acceleration, but others where precision cosmology is significant. In investigating this, we must get a clearer distinction between dynamical and observational effects - the latter not covered here, but certainly relevant to null fitting, which is the core of observational cosmology.

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

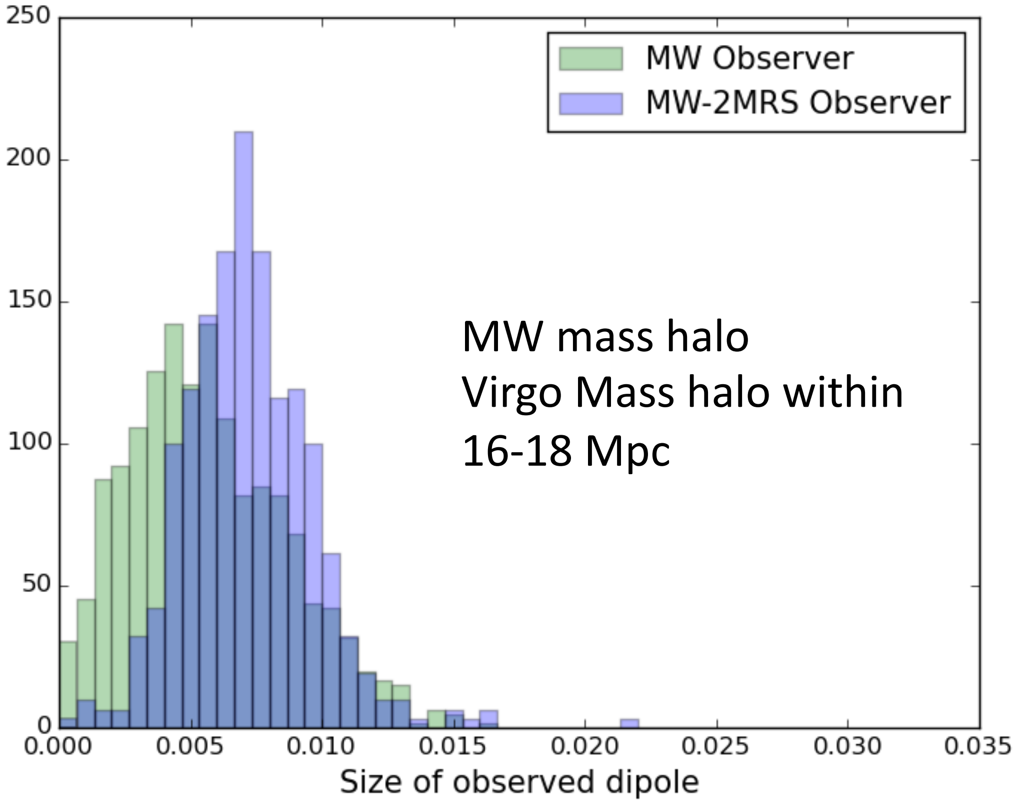
$\langle D_{cls} \rangle < 0.0018$
In the final sample

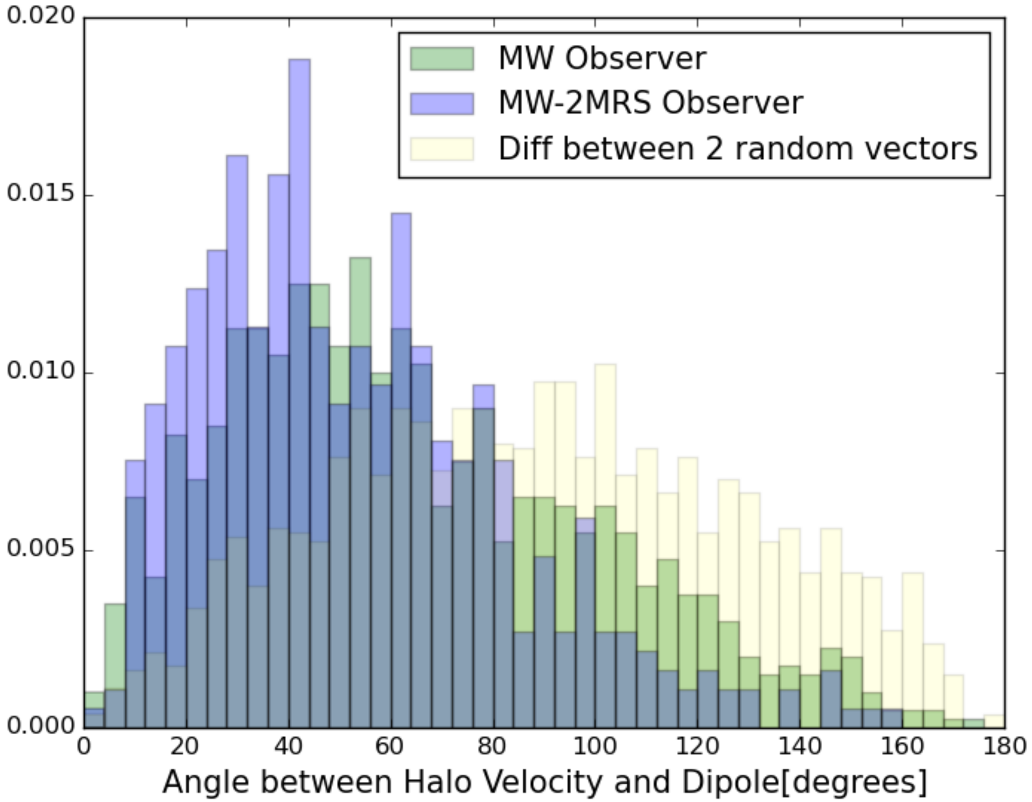
$D_{kin} = 0.0106$

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

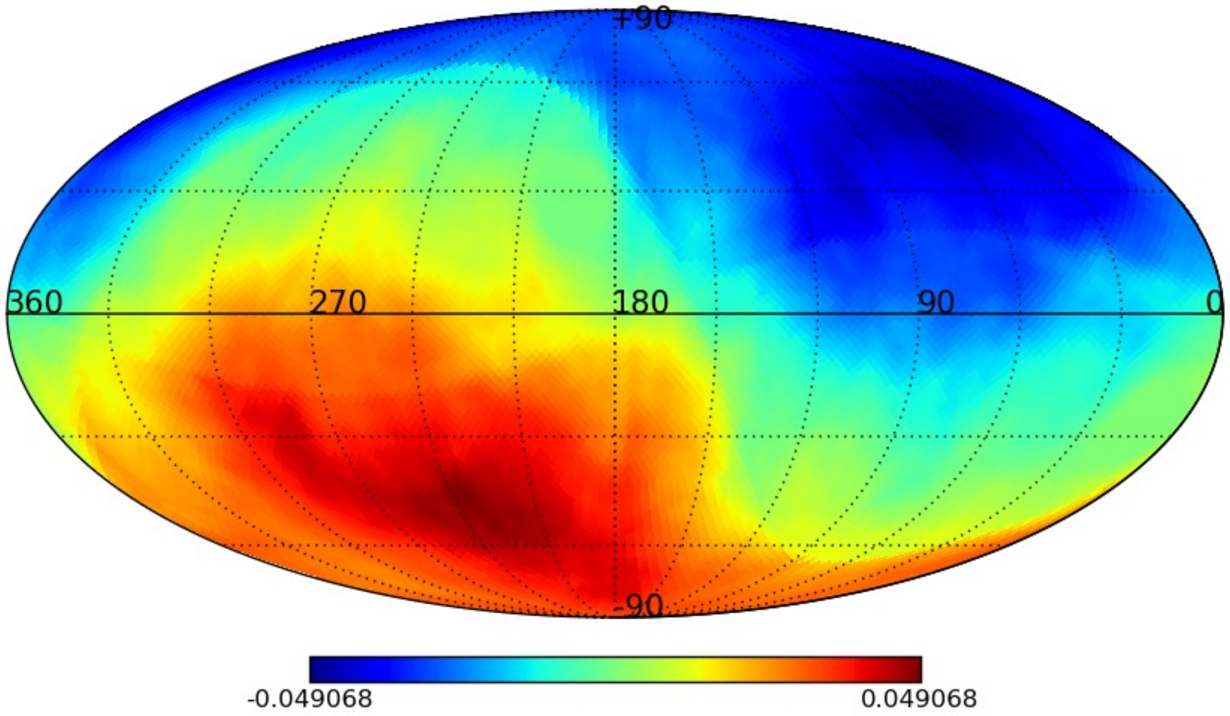
$\langle D_{cls} \rangle$ = 0.0076 +/- 0.0022

$\langle D_{kin} \rangle$ = 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

Cosmological perturbation theory

“solutions of the linearized field equations can be viewed as linearizations of solutions of the full non linear equations. ” Mukhanov, Feldman, Brandenberger 1991 , proof by P. D’Eath,Ann.Phys.98(1976)237.

Basically a taylor series expansion of EFE around FLRW

- R-W line element:

$$ds^2 = g_{\mu\nu} dx^\mu dx^\nu$$
$$= a(\tau)^2 \left[-d\tau^2 + \gamma_{ij}\left(x^k\right) dx^i dx^j\right]$$

- Perturbed R-W line element:

$$ds^2$$
$$= a^2(\tau)\{-(1 + 2\psi)d\tau^2 + 2w_i d\tau dx^i$$
$$+ \left[(1 - 2\phi)\gamma_{ij} + 2h_{ij}\right] dx^i dx^j\}$$

Allowed gauge conditions:

- ∇.w = 0 , ∇.h = 0

Instead if you set w = h = 0

Conformal Newtonian ‘gauge’

ψ and ϕ → Newtonian gravitational potential

This is how N-body simulations work

- “These conditions can be applied only if the stress-energy tensor contains no vector or tensor parts and there are no free gravitational waves, so that only the scalar metric perturbations are present. While this condition may apply, in principle, in the linear regime (|δρ/̄ρ| ≪1), nonlinear density fluctuations generally induce vector and tensor modes even if none were present initially. **In general, this is not a valid gauge condition— it is rather the elimination of physical phenomena** “ Bertschinger 1995

- Bulk flows - > Vector modes
  - , Durrer 2016

Our standard tools of cosmology: N-body simulations, CAMB etc are only (perhaps very) approximate descriptions of reality

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]

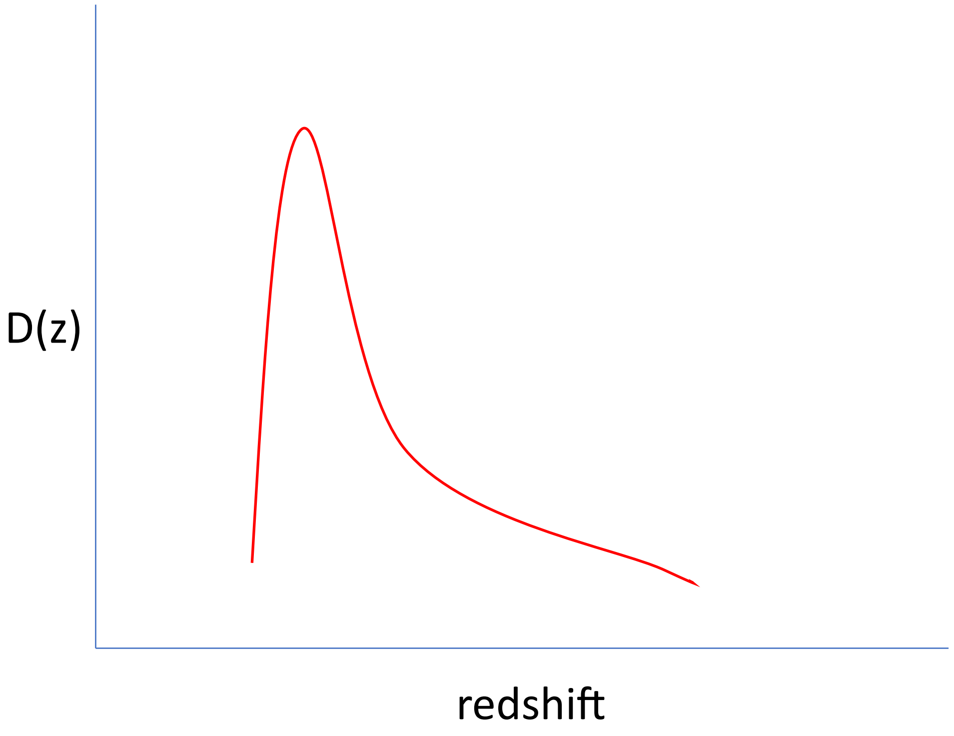
[1]Université de Lyon, Observatoire de Lyon, Centre de Recherche Astrophysique de Lyon, CNRS UMR 5574: Université Lyon 1 and École Normale Supérieure de Lyon, 9 avenue Charles André, F–69230 Saint–Genis–Laval, France
[2]Dipartimento di Fisica, Università degli Studi di Pavia, via A. Bassi 6, I–27100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

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



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

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

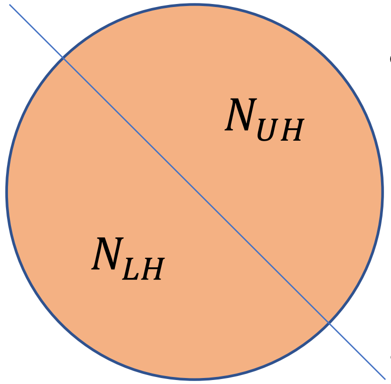
$\vec{\mathcal{R}} \rightarrow$ **The shot noise dipole,** $\propto 1/\sqrt{N}$, isotropic

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

$\vec{\mathcal{F}} \rightarrow$ **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

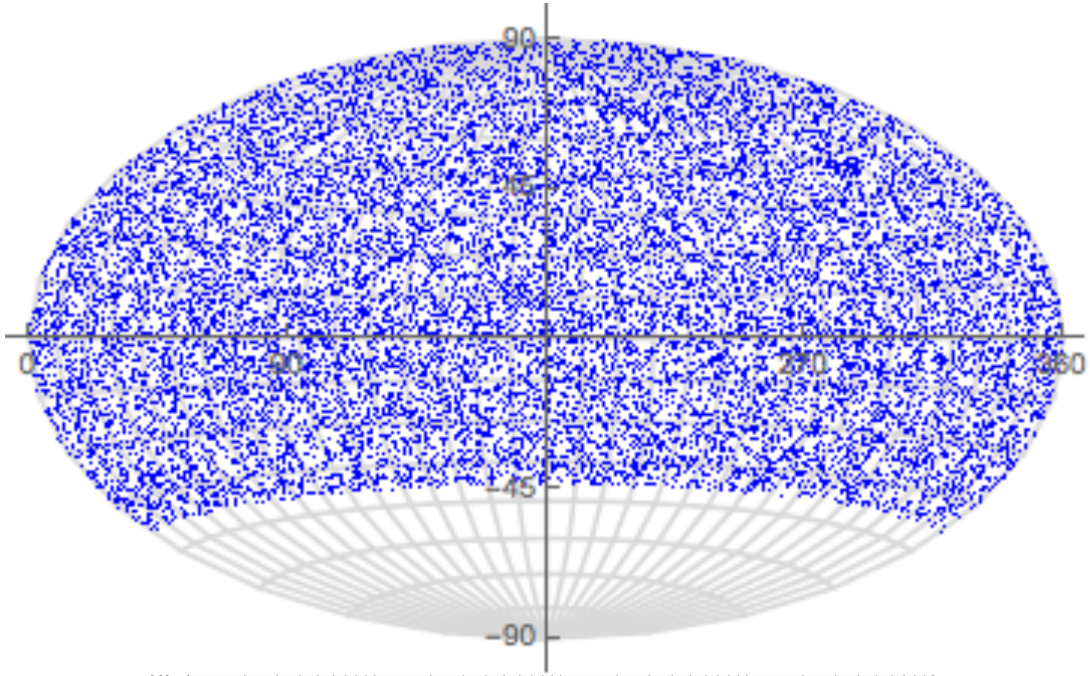
$$\frac{\left[n_p - \bar{n}\left(1 + \vec{D}_q.\hat{r}_p\right)\right]^2}{\bar{n}\left(1 + \vec{D}_q.\hat{r}_p\right)}$$

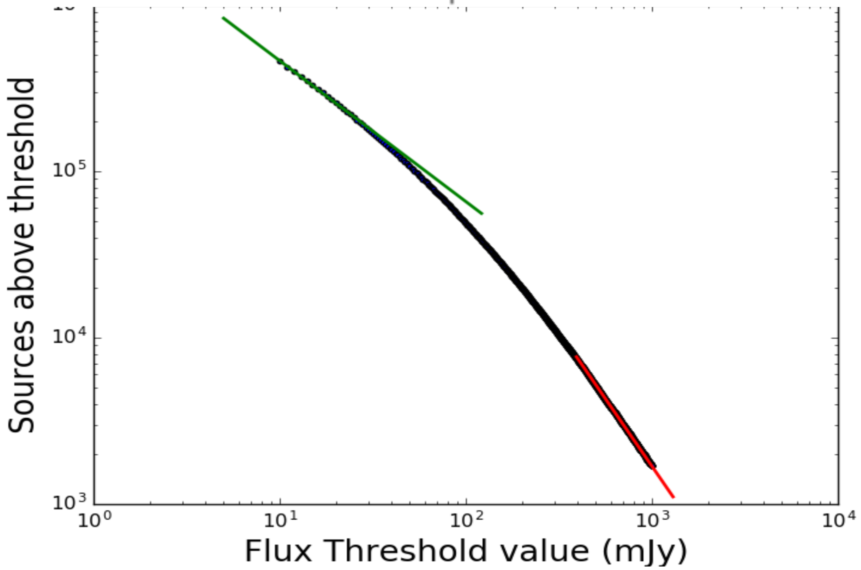
Minimize the above term, even less bias than the linear estimator

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

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

The NRAO VLA Sky Survey (NVSS)



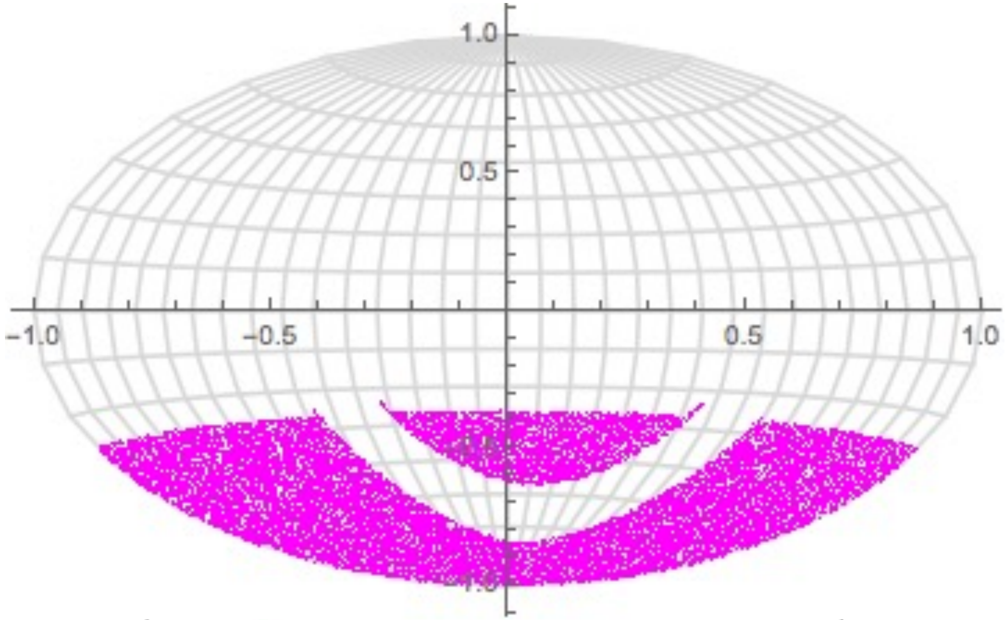


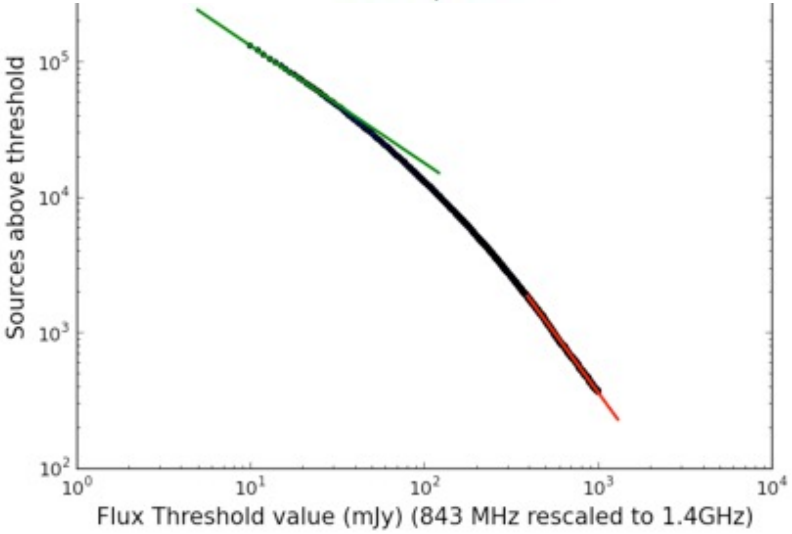
1.4 GHz survey of the Northern sky, by the National Radio Astronomy Observatory. Down to dec = -40.4^o

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

Phys. Rev. D, 78, 043519

Sydney University Molonglo Sky Survey (SUMSS)





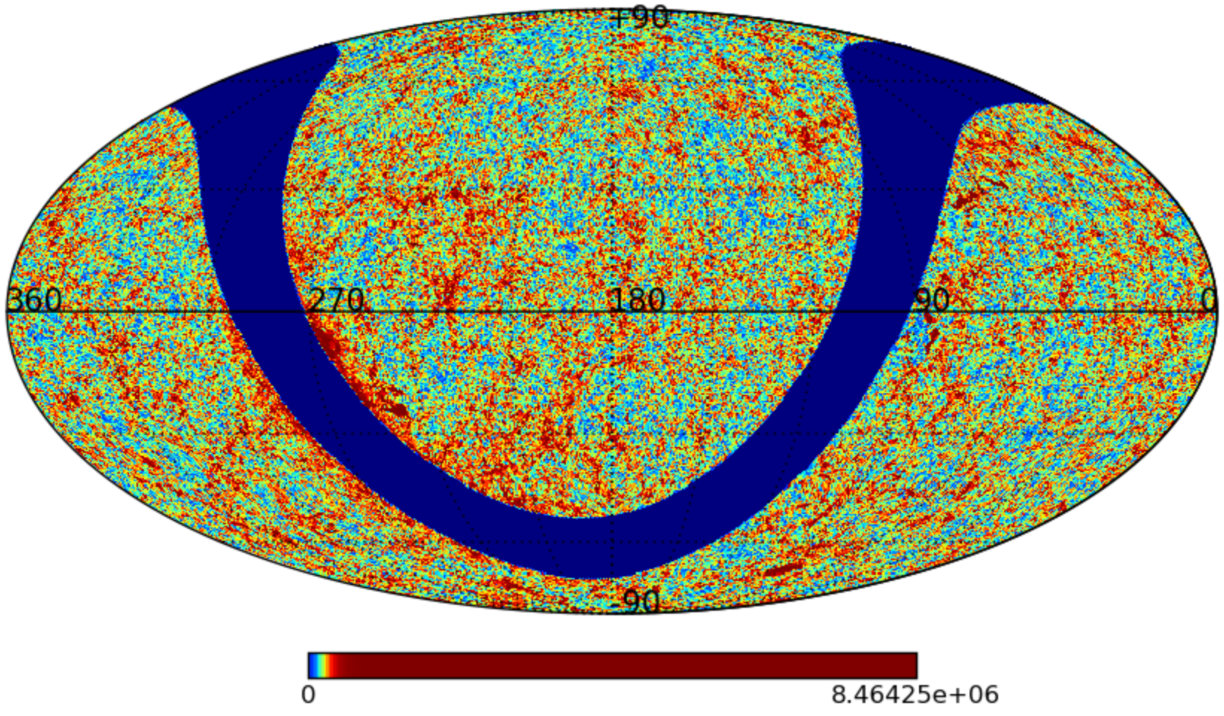
843 MHz survey of the Southern sky, by the Molonglo Observatory Synthesis telescope. Dec < -30.0^o

211050 radio sources. Similar sensitivity and resolution to NVSS

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

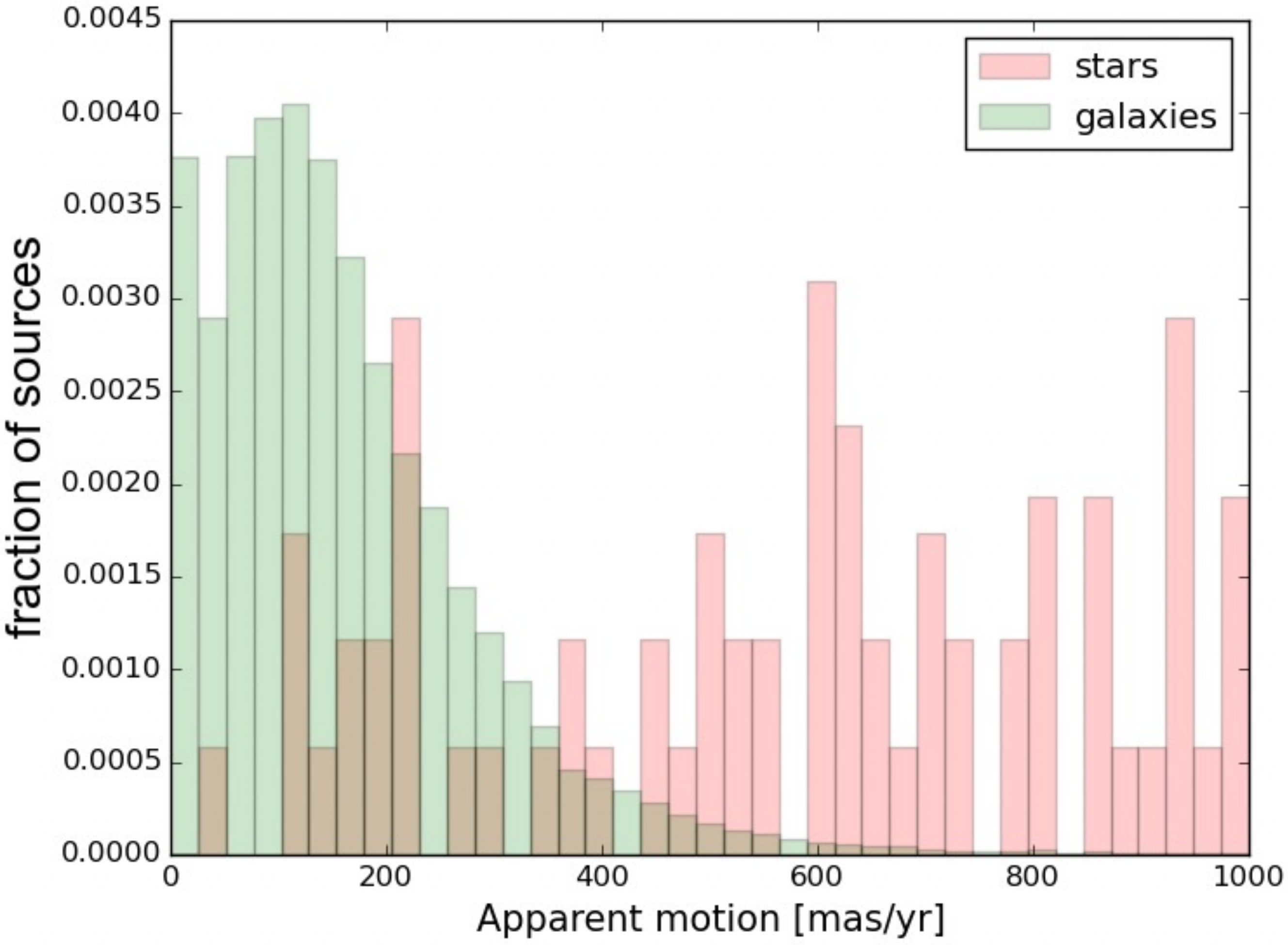
110 degrees from the CMB direction

Dipole magnitude ~0.049

Fully kinematic interpretation ~6000 km/s

in agreement with MNRAS 445 (2014) L60-L64

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

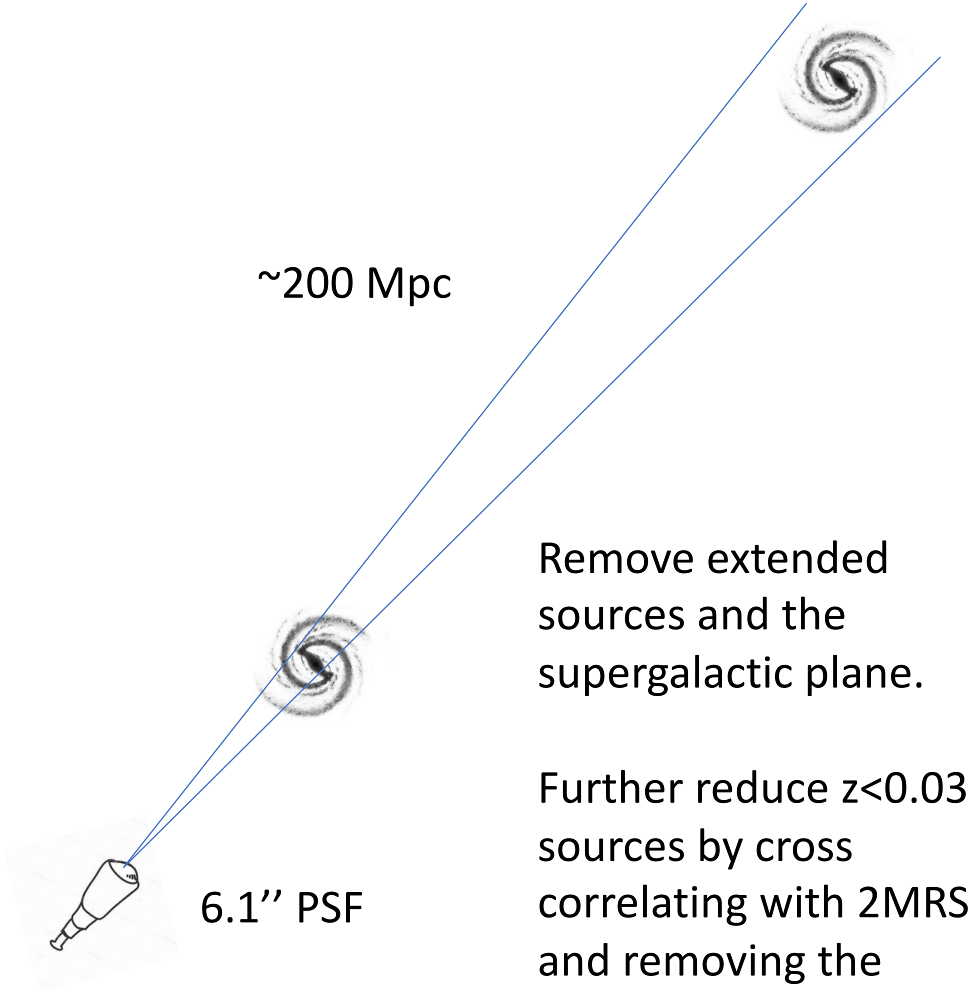
Cuts on apparent motion can bring star contamination down to 0.1%, while still keeping ~1.8 millin galaxies.

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

Dipole magnitude reduces to 0.014

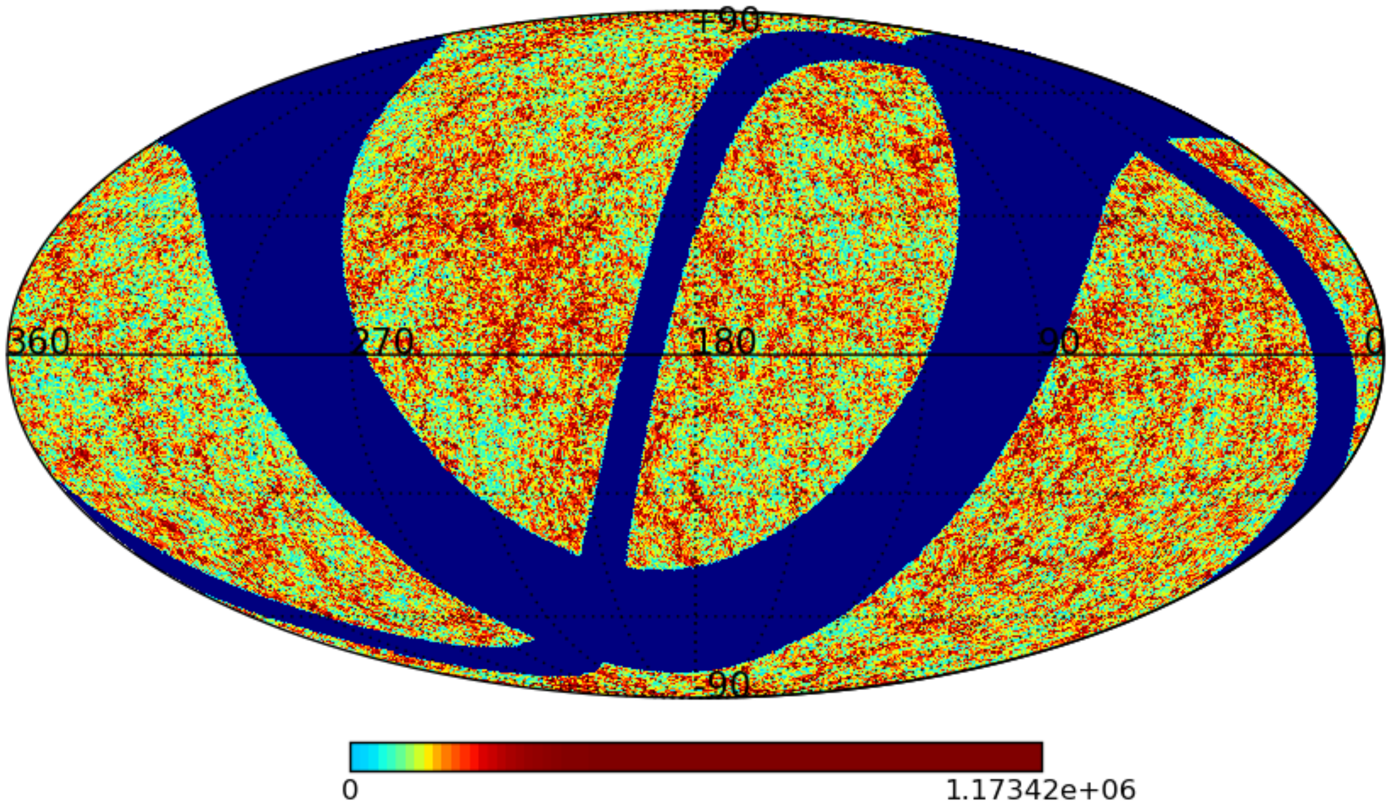
Star galaxy identification by cross correlating with SDSS

Suppressing local anisotropies

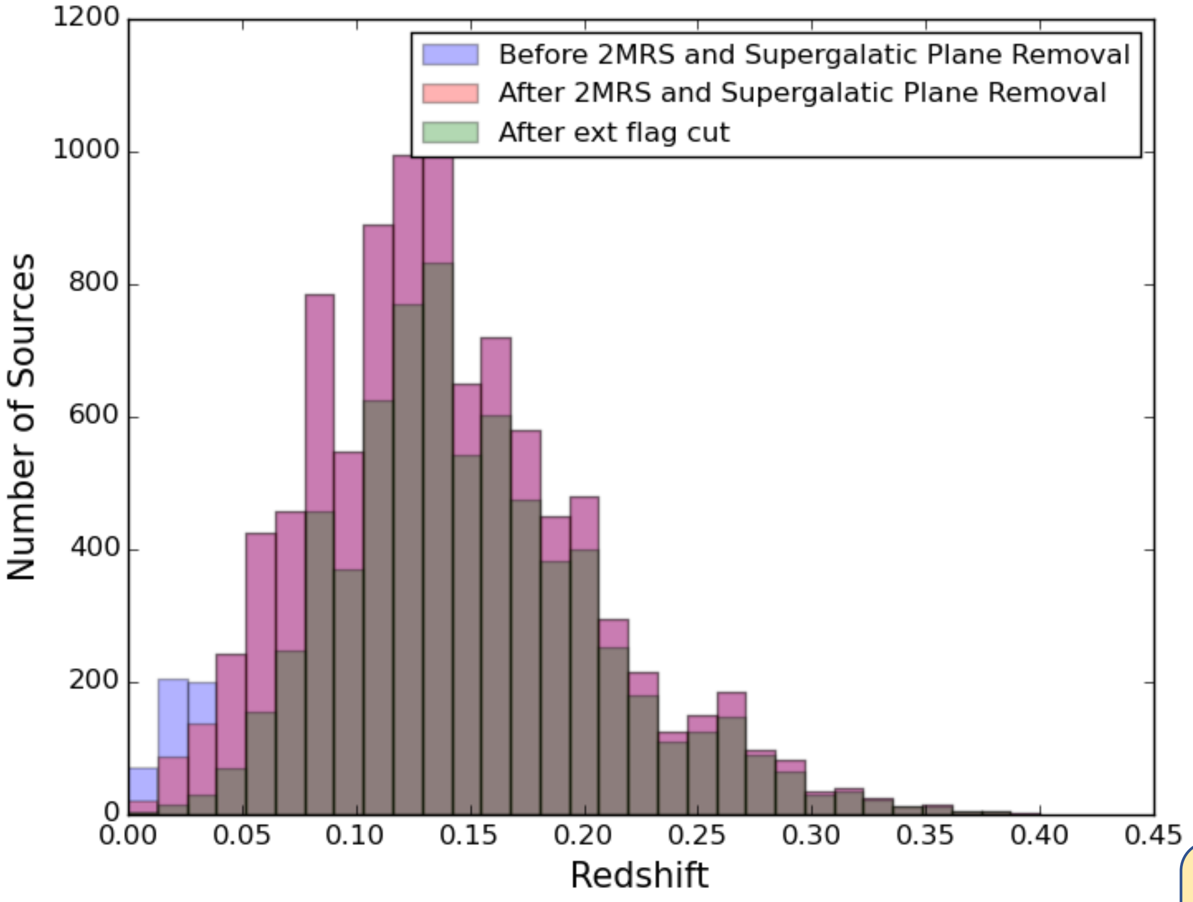


Remove extended sources and the supergalactic plane.

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



Results

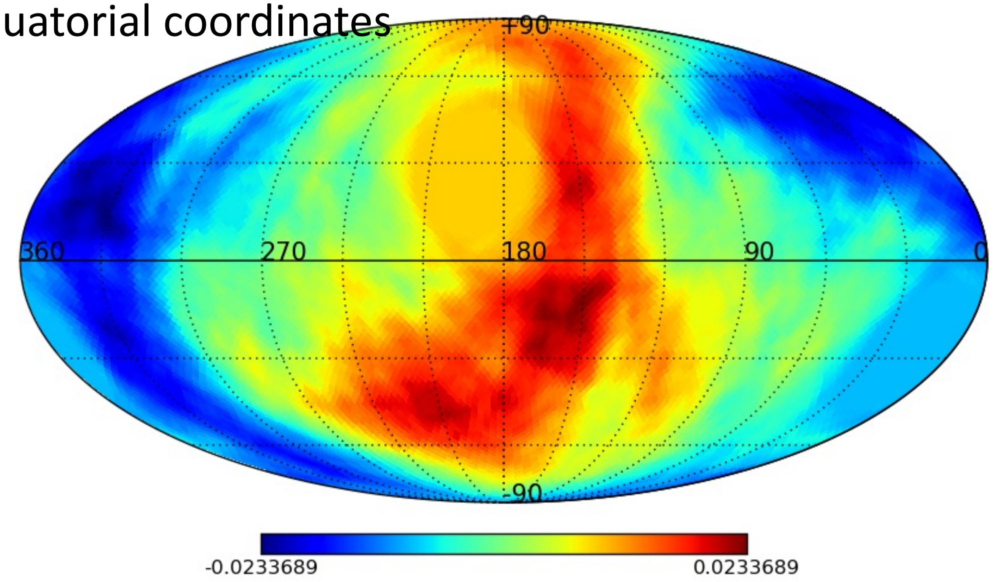


d = 0.0124 > 3600 km/s if fully kinematic

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

Total dipole is at least 4.6σ statistically significant.

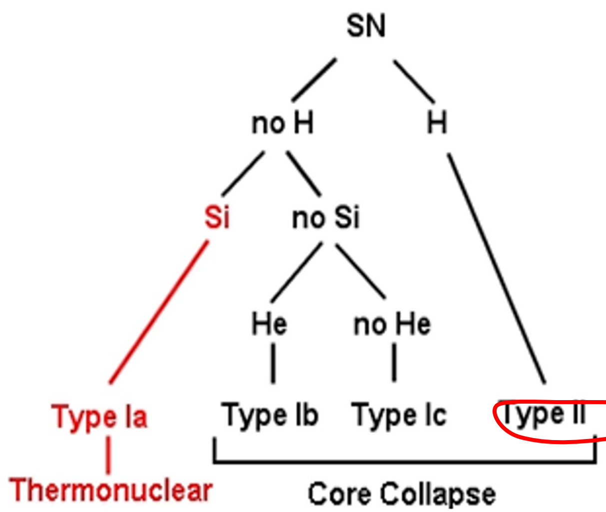
Equatorial coordinates

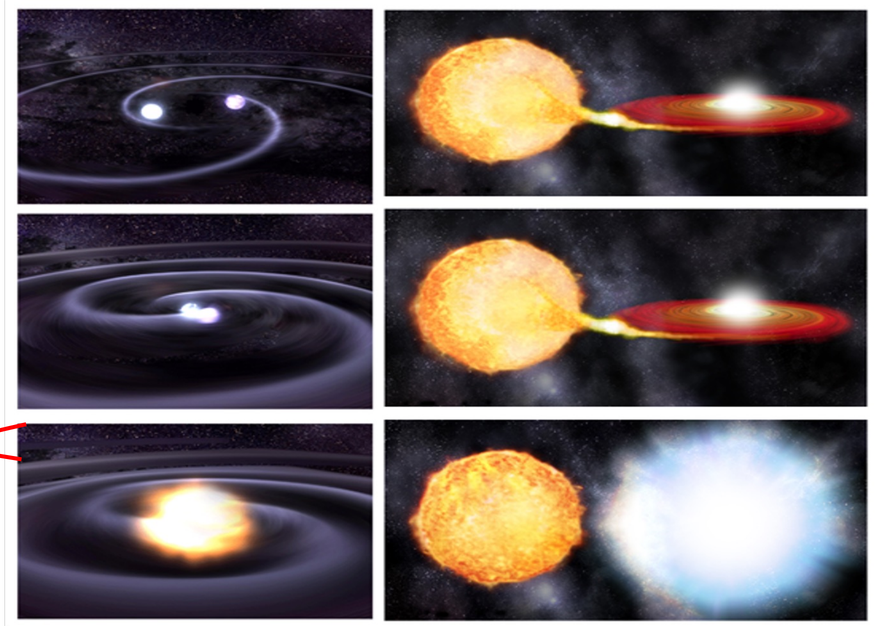


By cross correlating with Galaxy and Mass Assembly

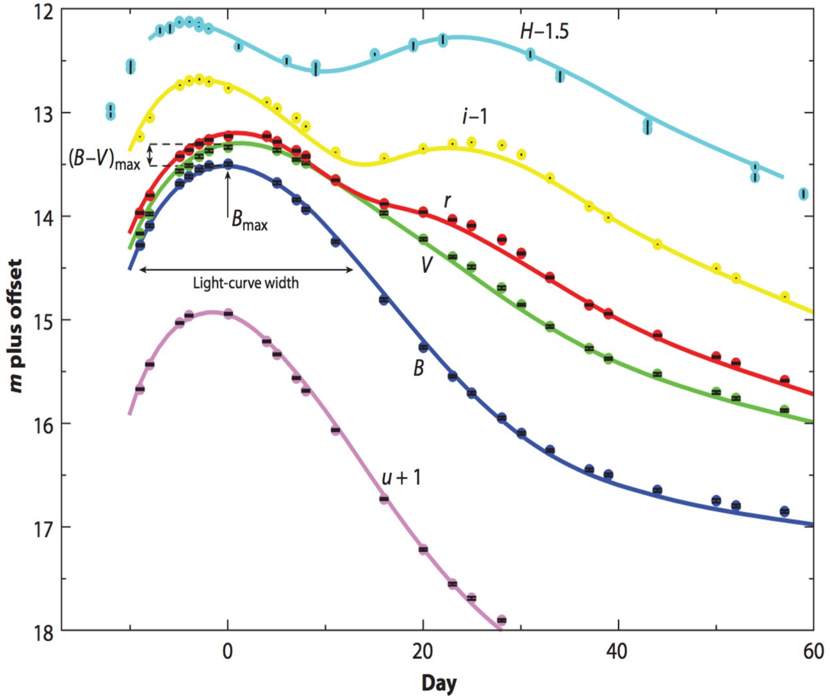
V = 1260 $\pm$ 629 km/s within 6 degrees of CMB dipole
After removing the clustering dipole according to LCDM

What are Type Ia supernovae?

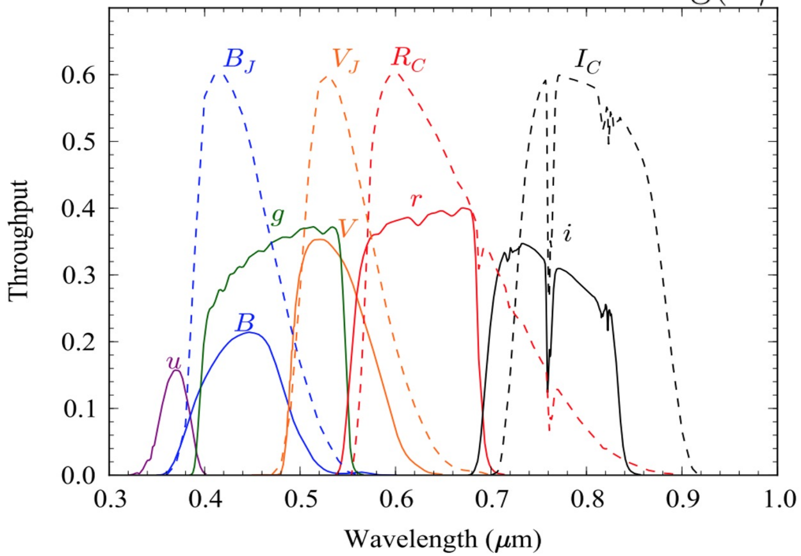




A white dwarf accreting matter from a binary companion, reignites when crossing ~1.44 Solar Masses

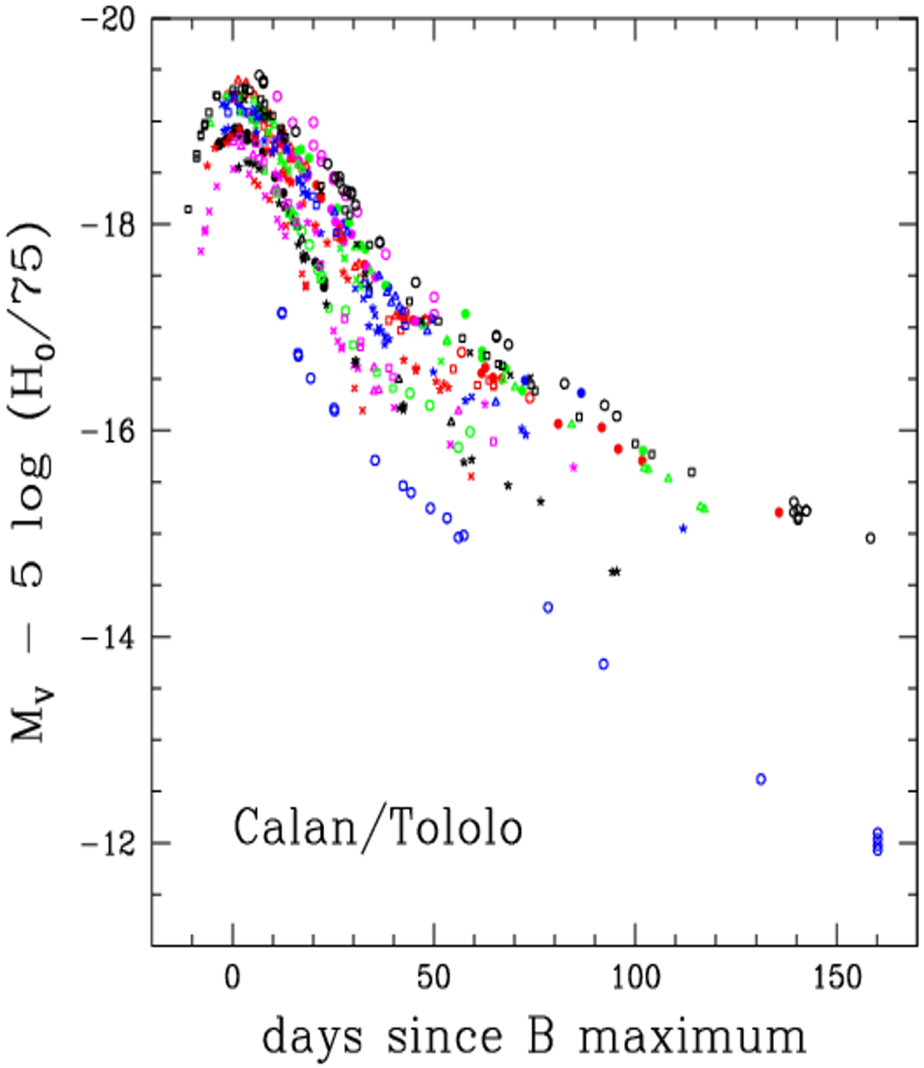


$$m = -2.5\log(F/F_{\rm ref})$$

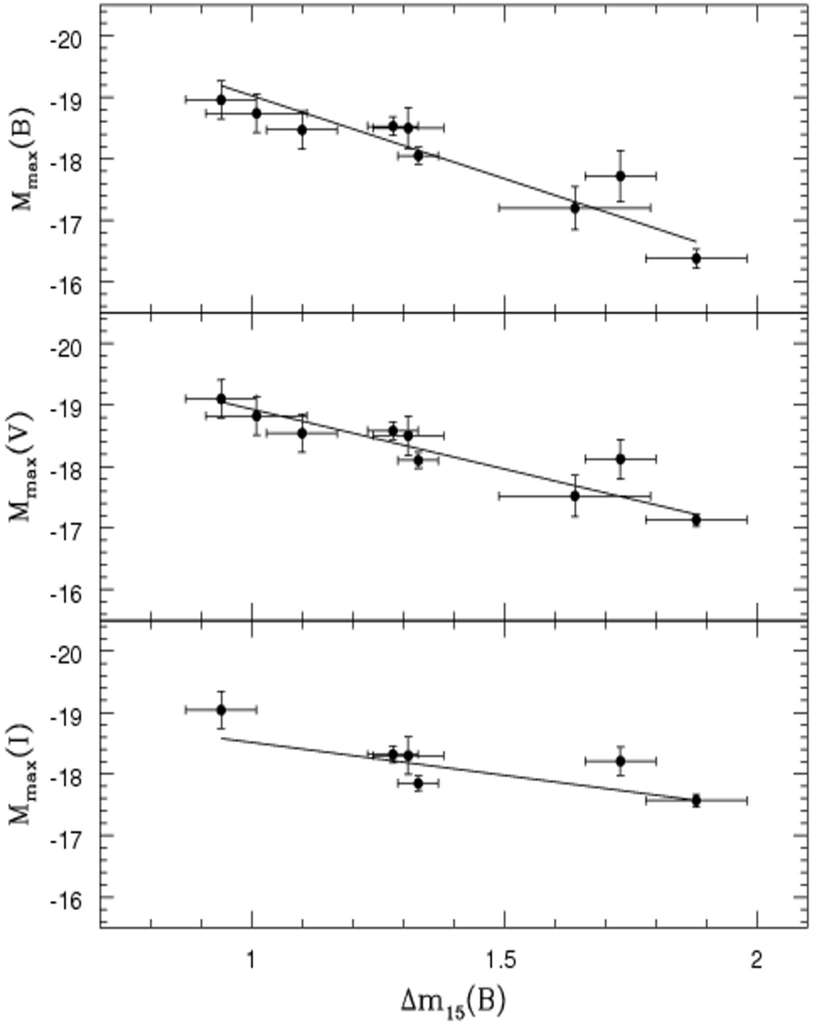


Goobar & Leibundgut, arXiv:1102.1431

THEY ARE CERTAINLY *NOT* 'STANDARD CANDLES'



Hamuy, arXiv:311.5099

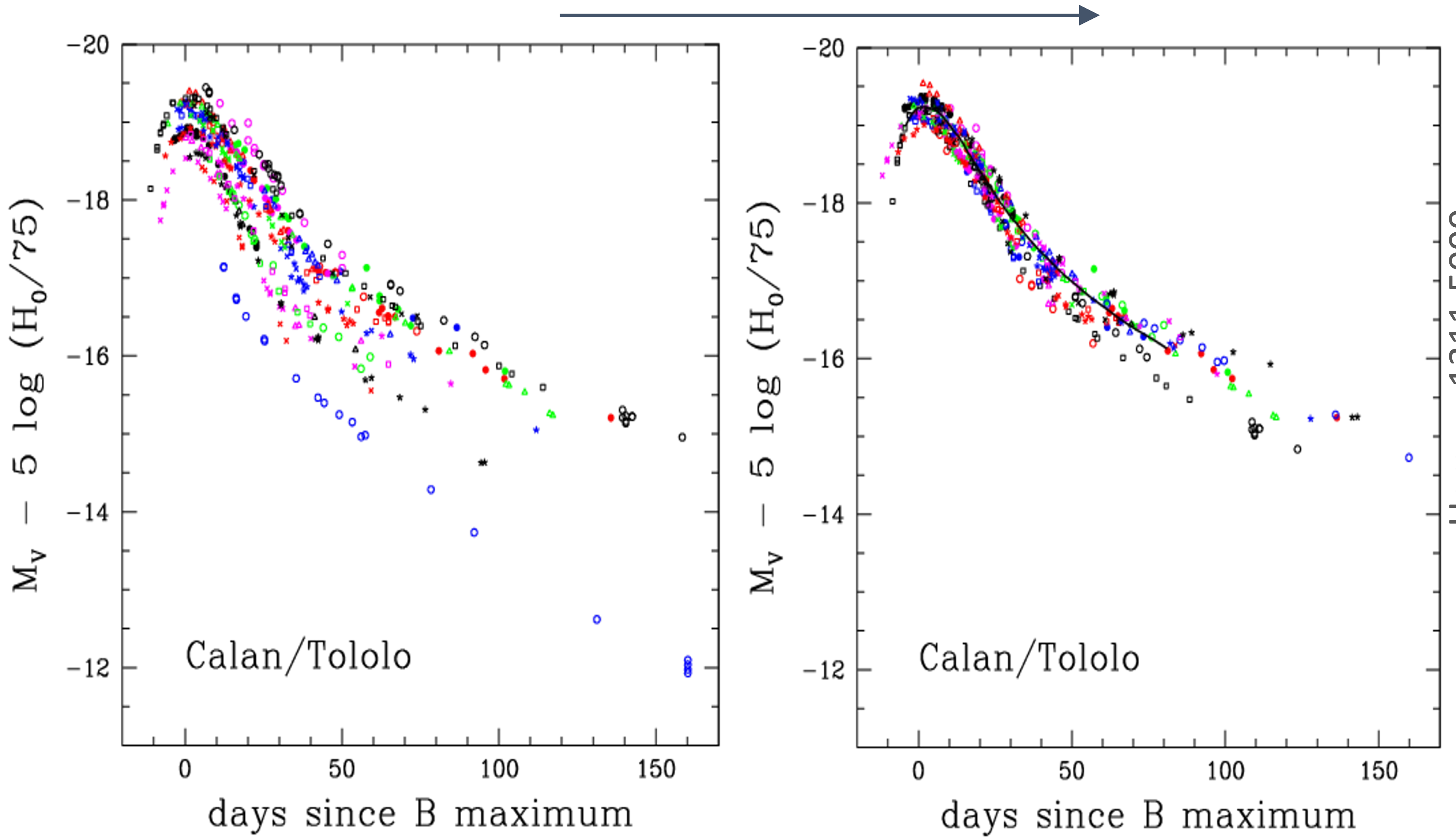


Phillips, ApJ **413**:L105, 1993

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



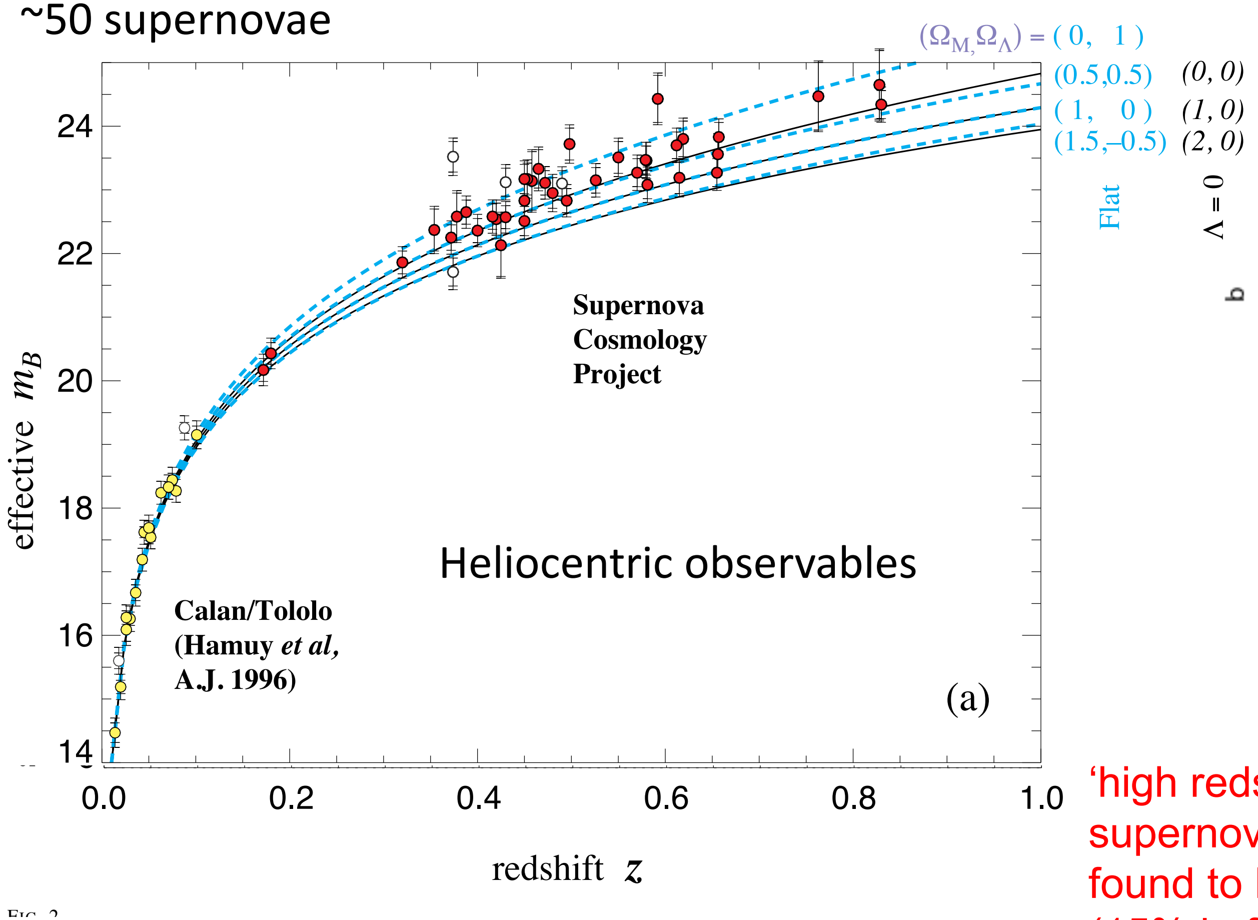
Hamuy, 1311.5099

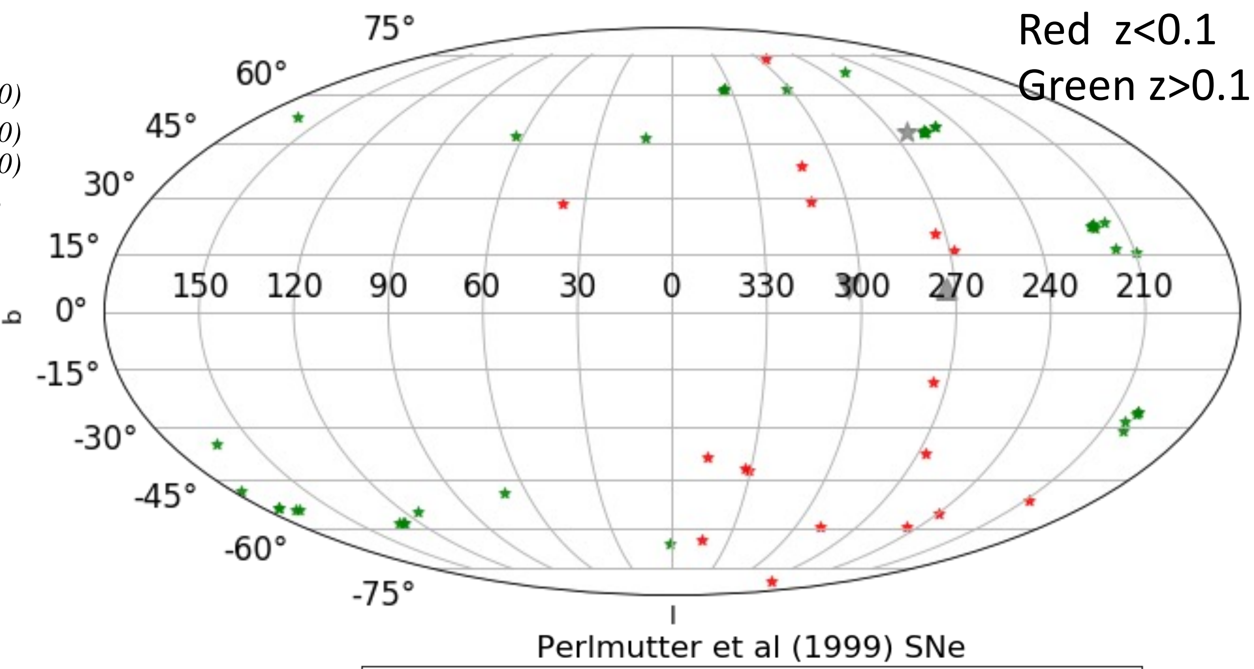
Distance modulus $\mu_B = m_B^* - M + \alpha X_1 - \beta \mathcal{C}$ $= 25 + 5\log_{10}\frac{d_L}{Mpc}$

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

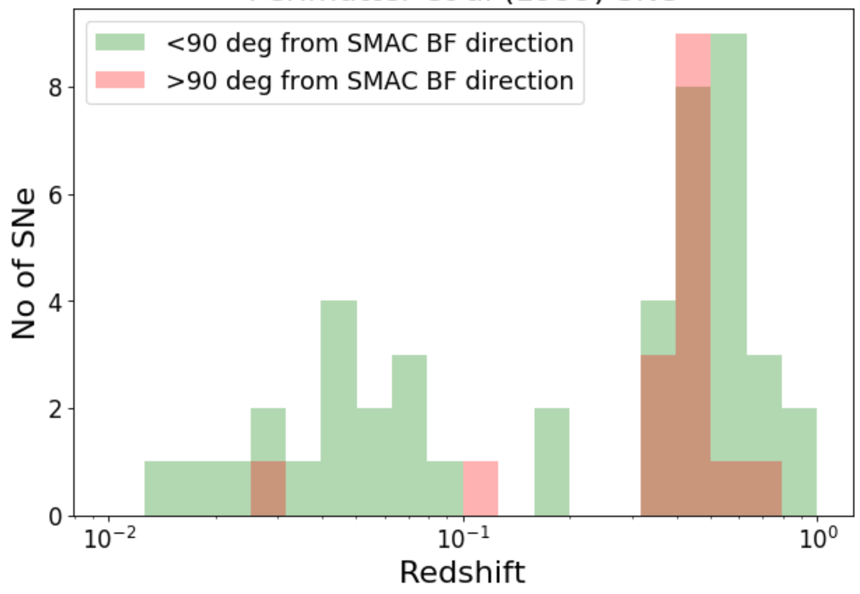
Supernova data fitting, a history

~50 supernovae





Red z<0.1
Green z>0.1



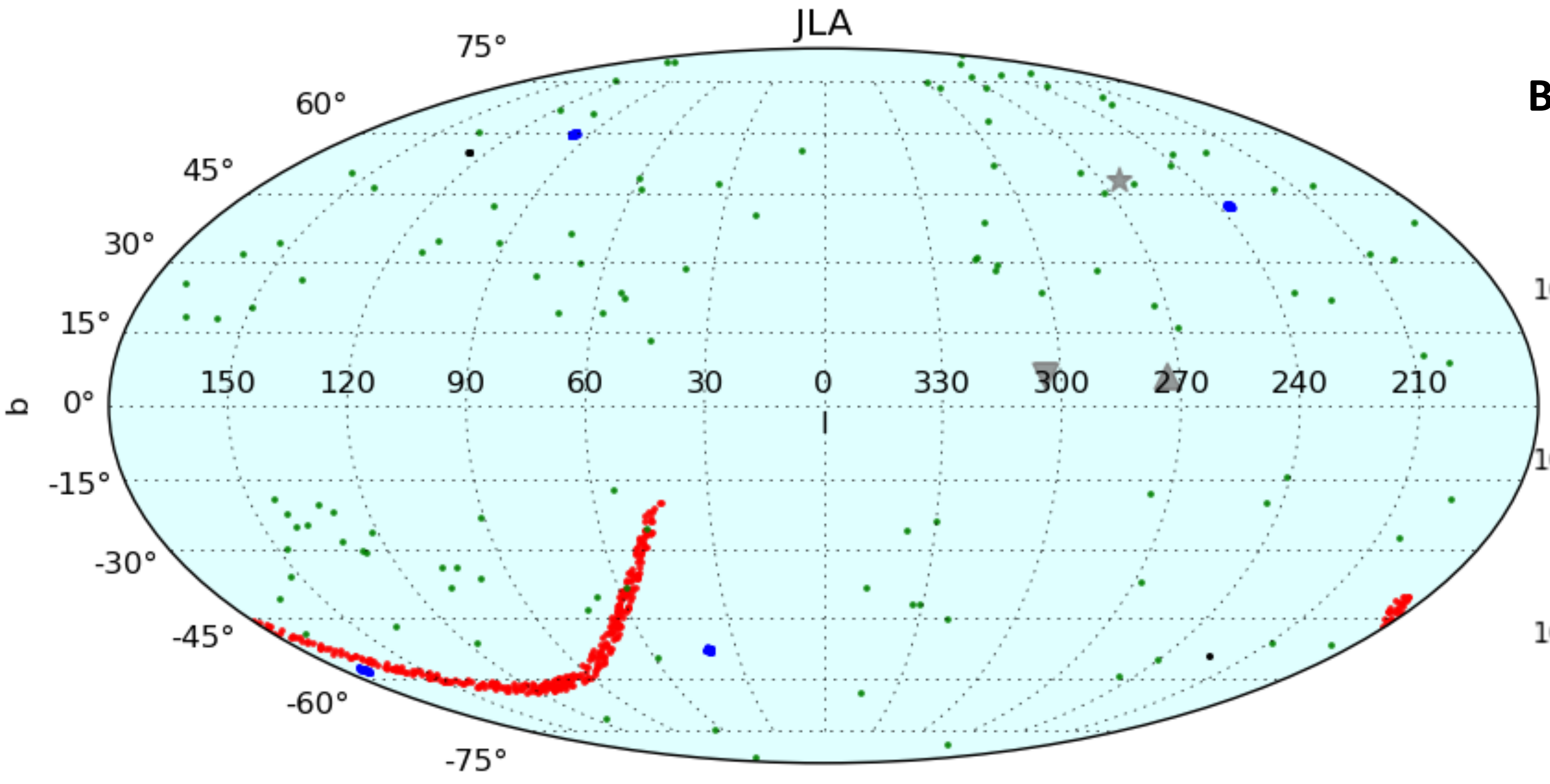
Perlmutter et al 1999 :
The data have intrinsic scatter:

$$\chi^2_\mu = \Sigma \frac{(\mu_i - \mu_{obs})^2}{\left(\sigma^{fit}_{\mu,i}\right)^2 + \left(\sigma^{z}_{\mu,i}\right)^2 + (\sigma^{int}_\mu)^2}$$

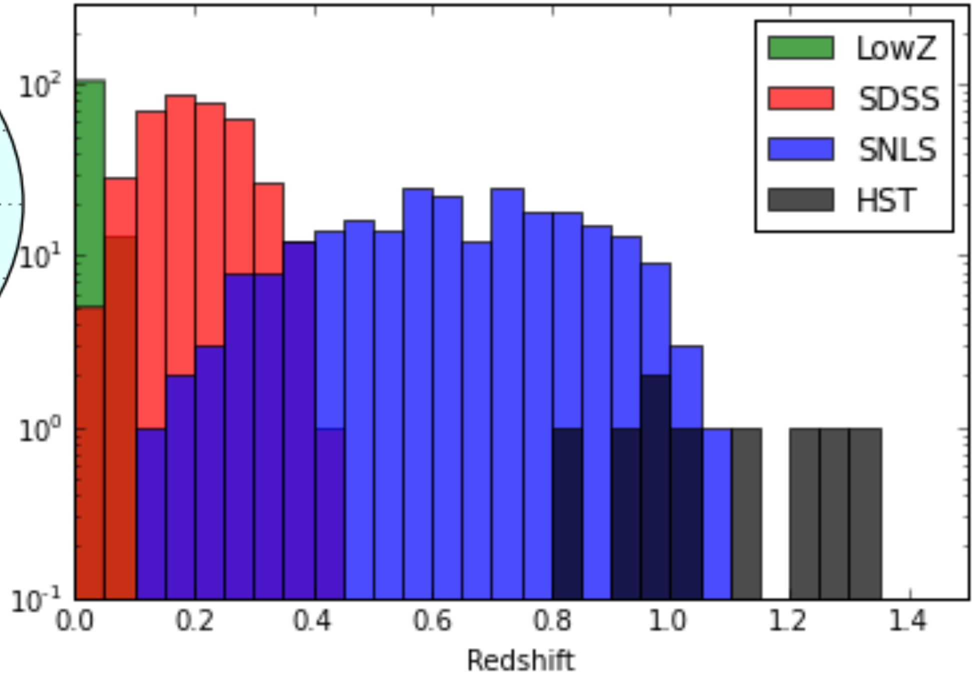
σ^{int}_μ is usually adjusted until a χ^2_μ/dof ~1 is obtained

'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)'

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

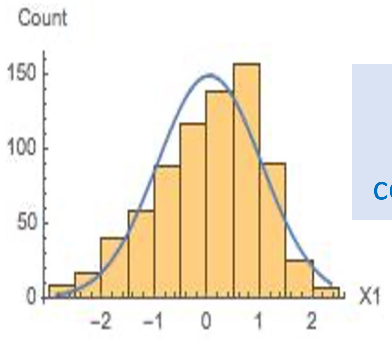
There may well be other variables that the magnitude correlates with …

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

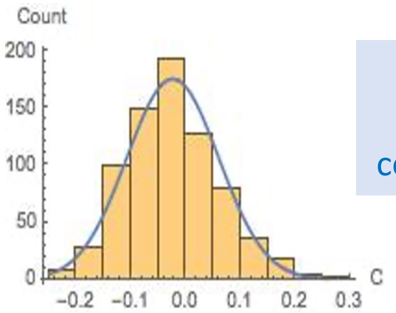
$$\mathcal{L} = \text{probability density}(\text{data}|\text{model})$$

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

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

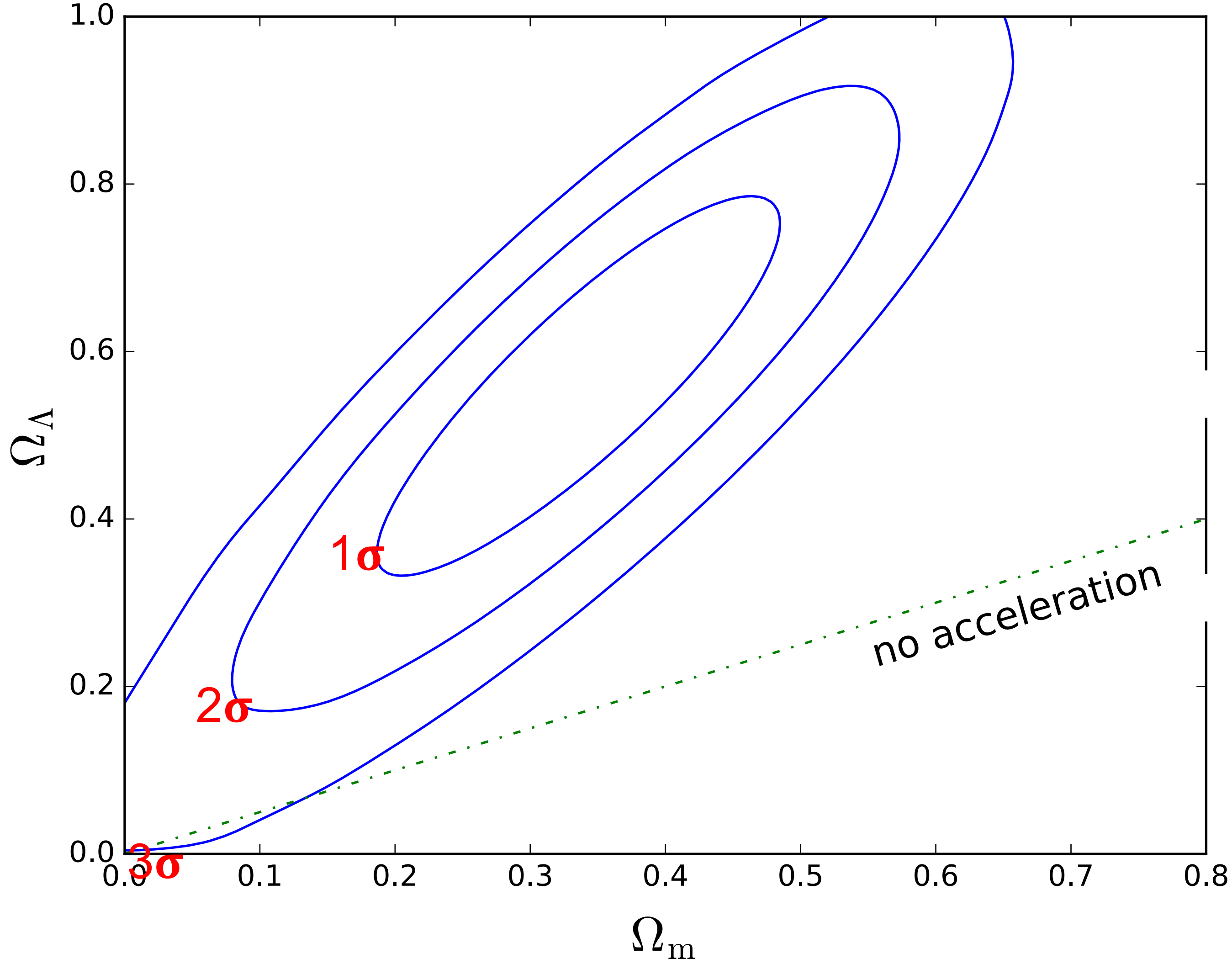
c_0

σ_{c_0}

M_0

σ_{M_0}

Data consistent with uniform expansion @<3σ!



profile likelihood

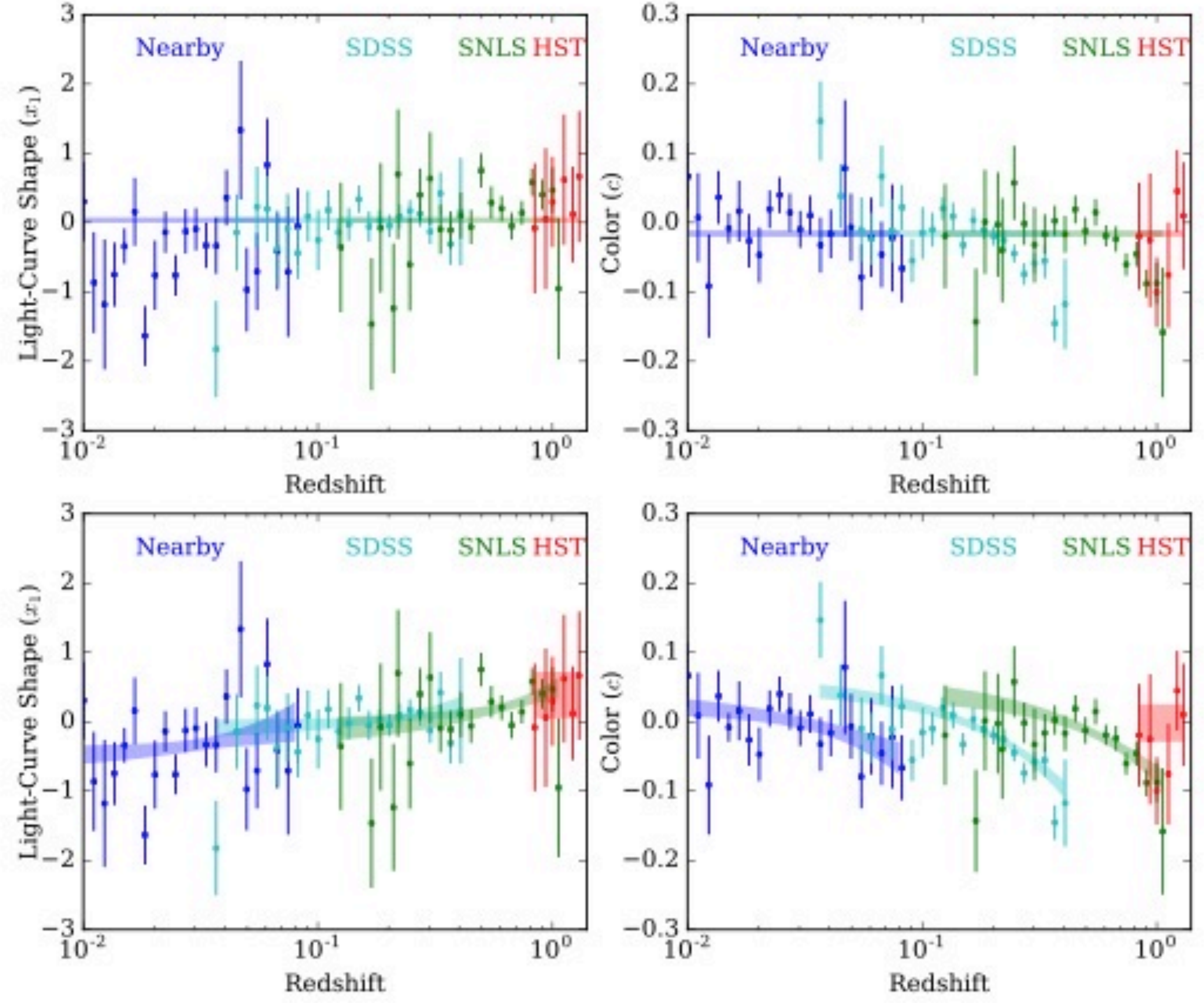
<u>MLE, *best fit*</u>

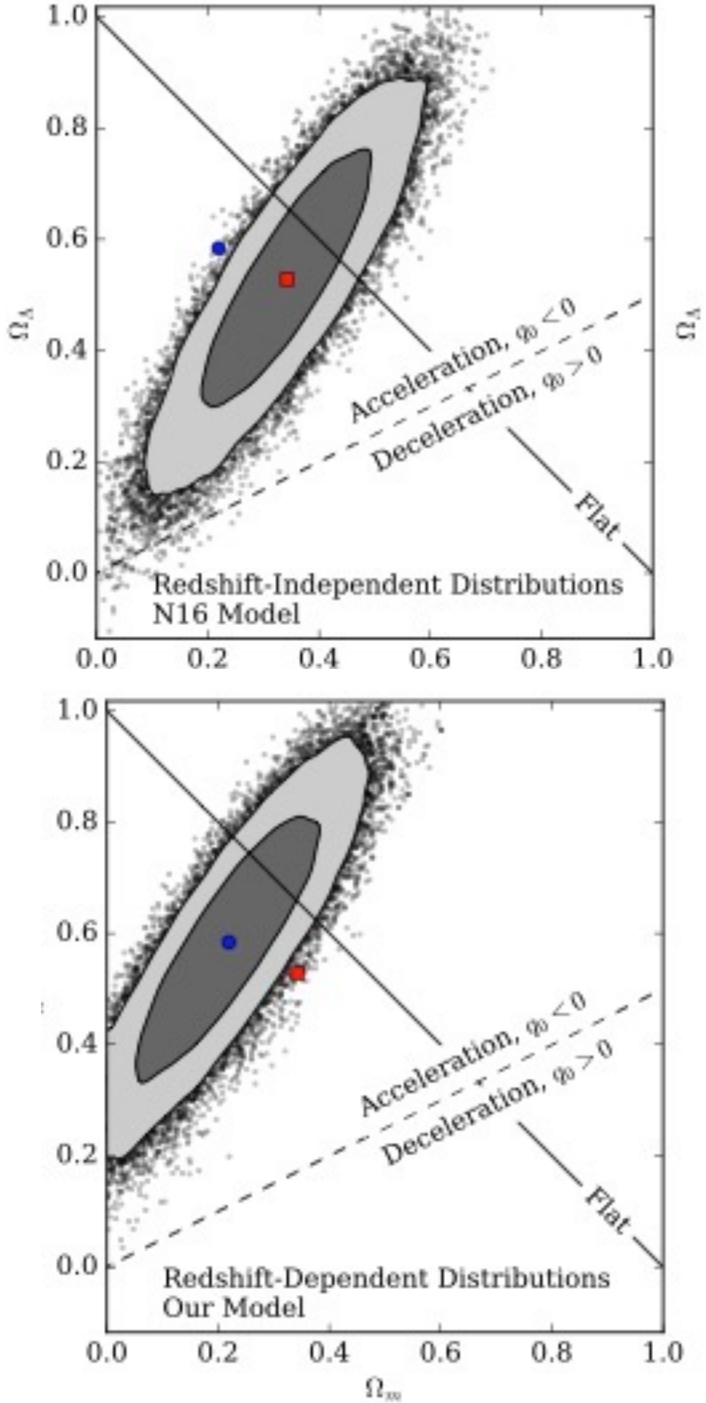
Ω_M	0.341
Ω_Λ	0.569
α	0.134
x_0	0.038
σ^2_{x0}	0.931
β	3.058
c_0	-0.016
σ^2_{c0}	0.071
M_0	-19.05
σ^2_{M0}	0.108

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

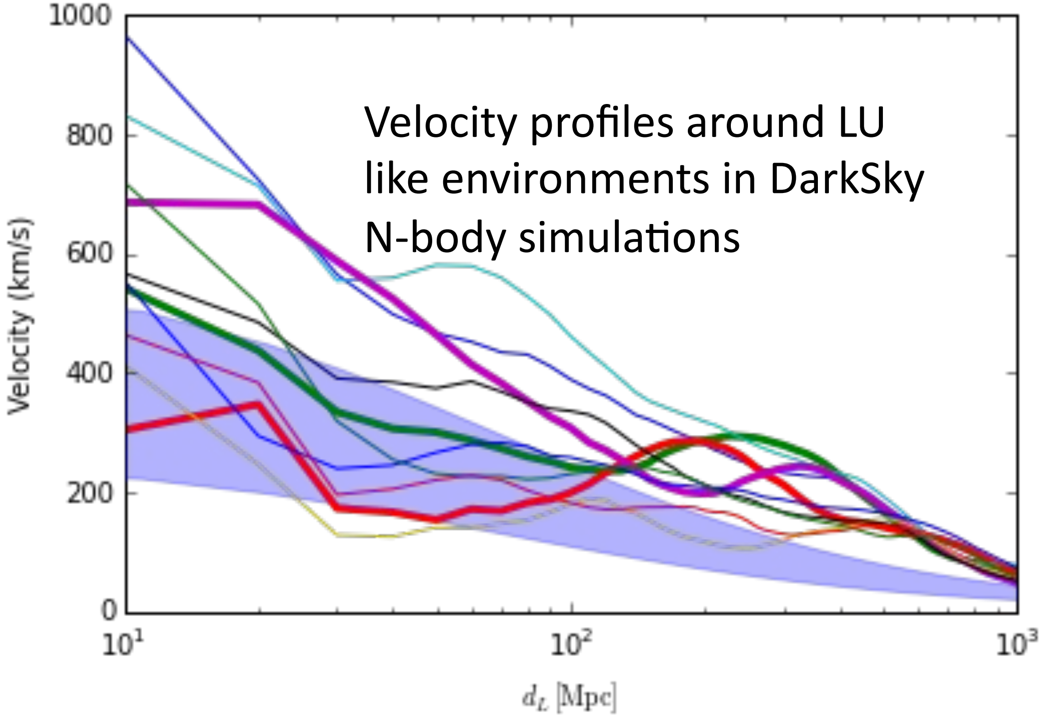
$$1 + z = (1 + \bar{z})\left(1 + z_{pec}^{hel}\right)\left(1 + z_{pec}^{SN}\right)$$
$$d_L(z) = \bar{d}_L(\bar{z})\,\left(1 + z_{pec}^{hel}\right)\left(1 + z_{pec}^{SN}\right)^2$$

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
03D1fq 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

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

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

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

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:**

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

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