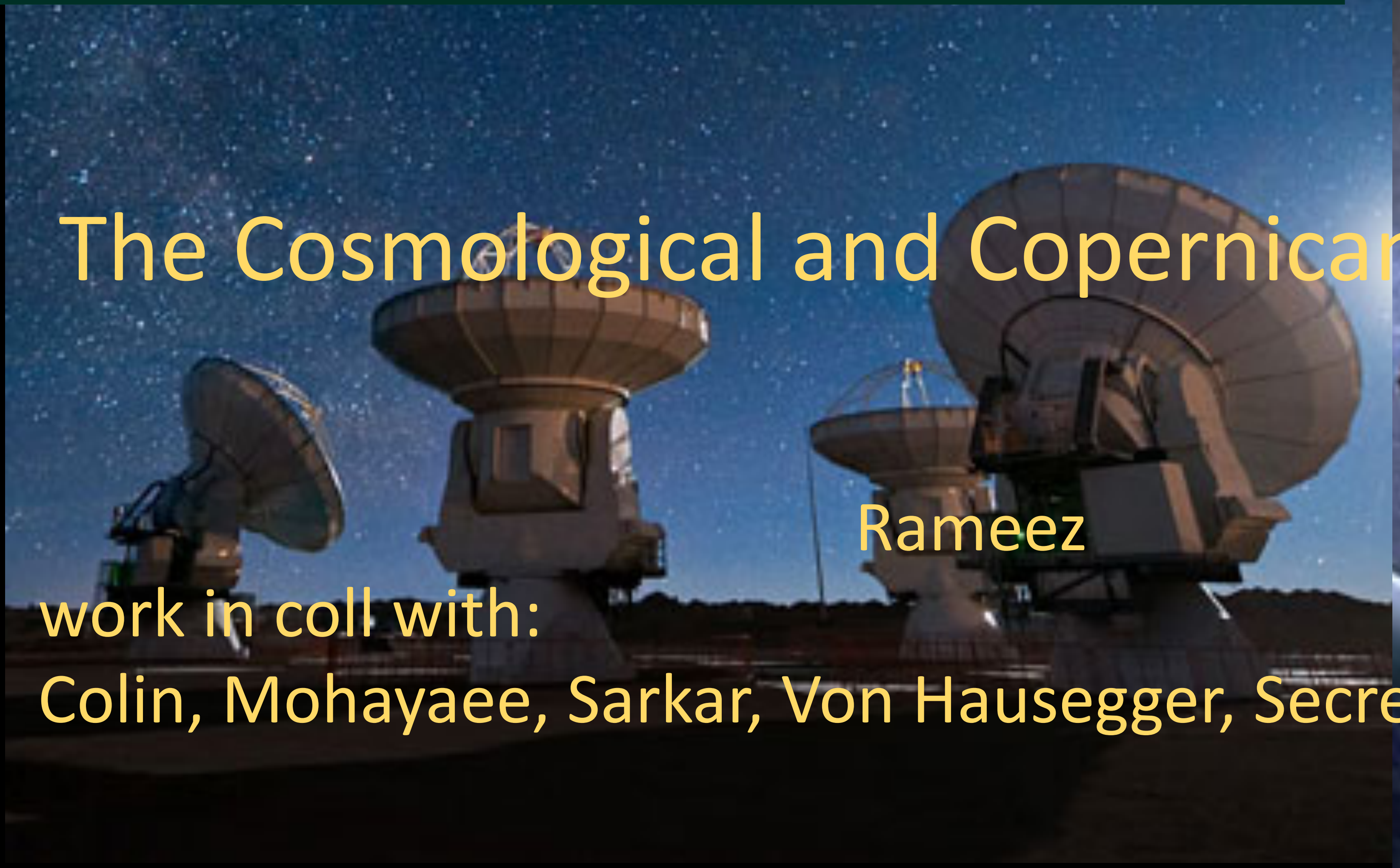
CARLSBERGFONDET



The Cosmological and Copernican principles

Rameez

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

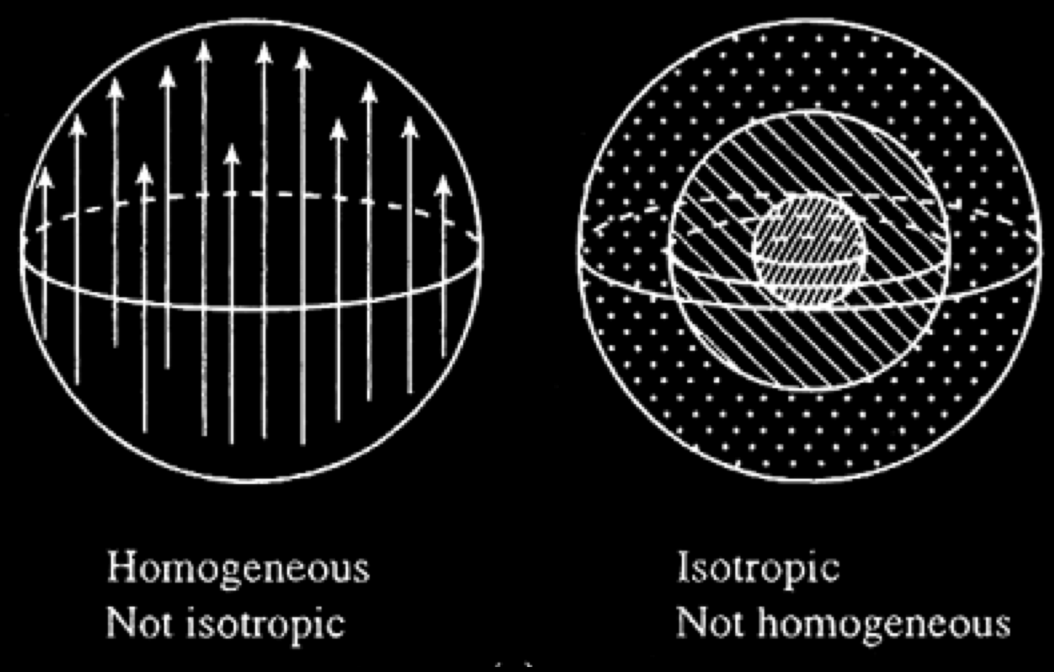
The Niels Bohr International Academy

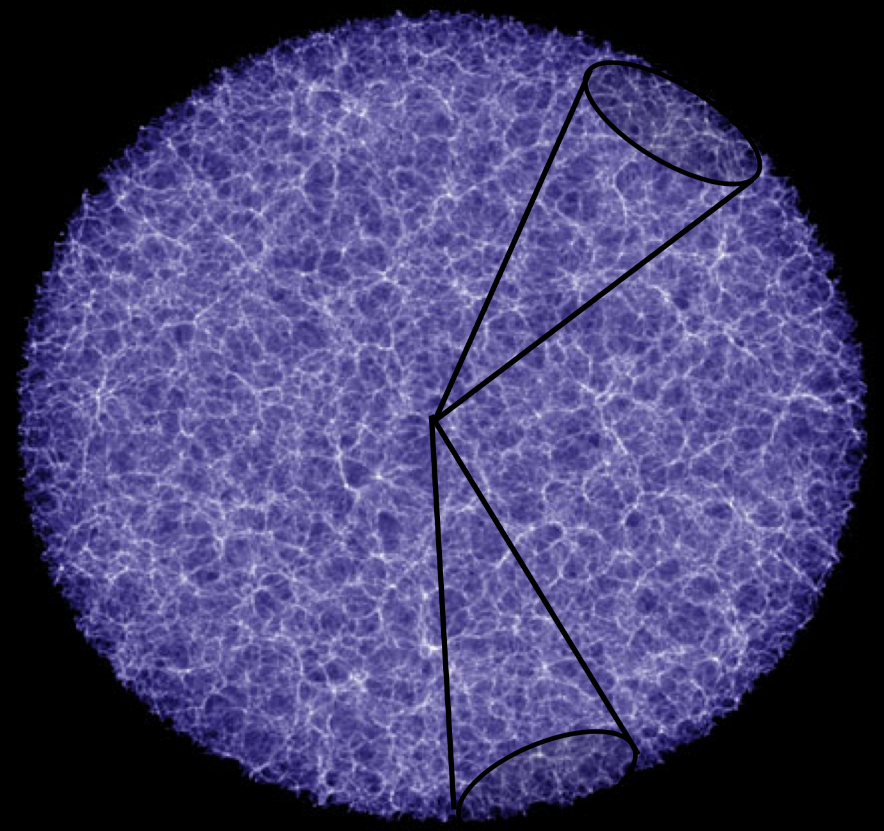
UNIVERSITY OF COPENHAGEN

CoSyne
Paris, December 2019

The cosmological principle

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





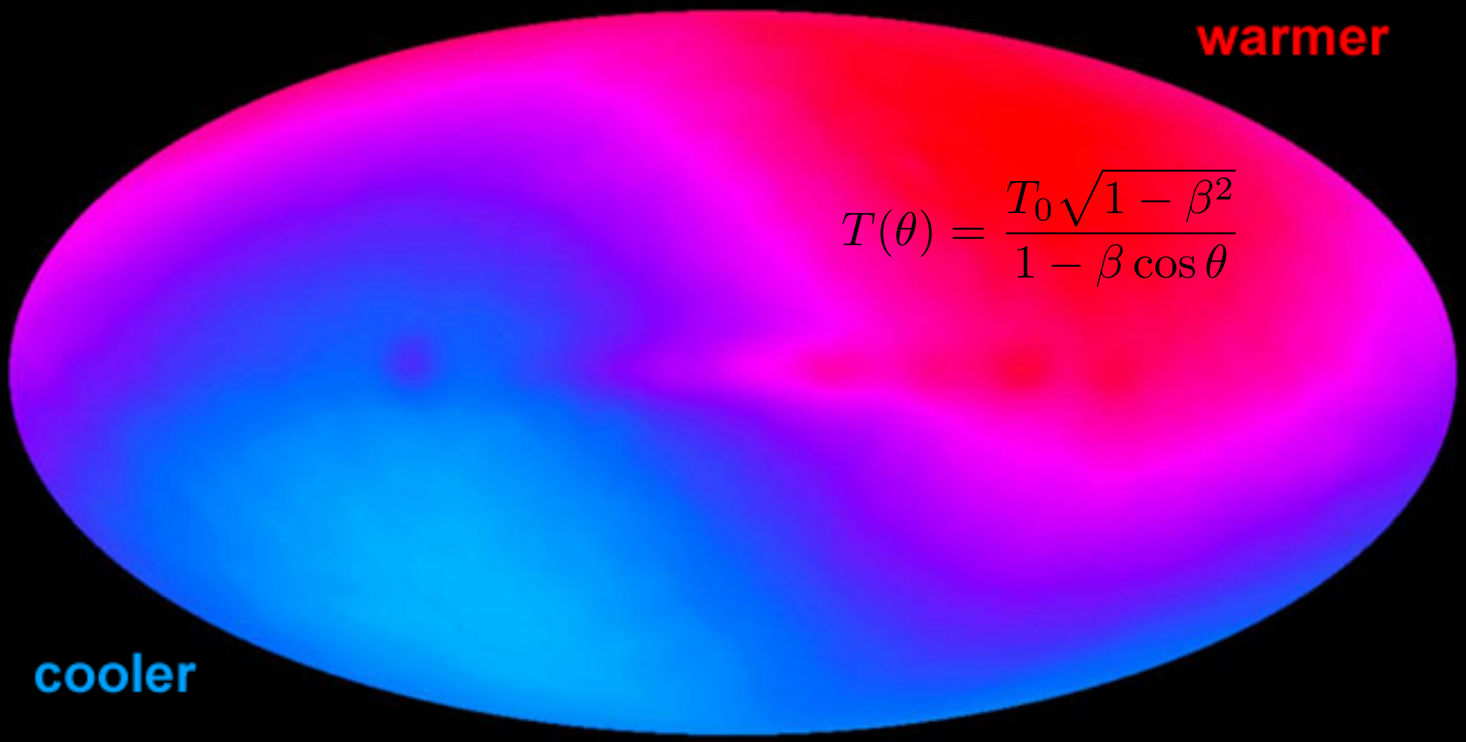
No special positions or directions in the Universe.
Goes back to Newton's Principia Mathematica

Also the Copernican principle :
we are 'typical' observers: a rather vague idea

'Stationary' observer:

- Sees same number of sources per solid angle in all directions
- Large angles, deep enough survey

The CMB Dipole: Our motion through the cosmos?



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

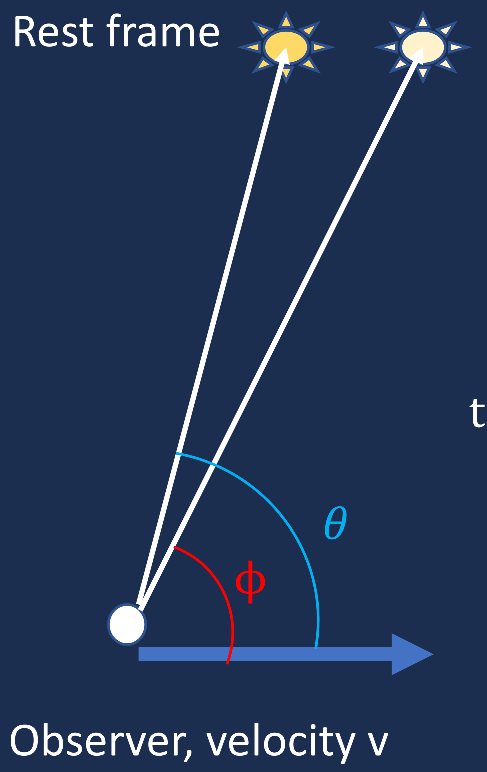
What is the origin of this motion?

A moving observer - Kinematic Dipole

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

Ellis & Baldwin (1984)

Aberration



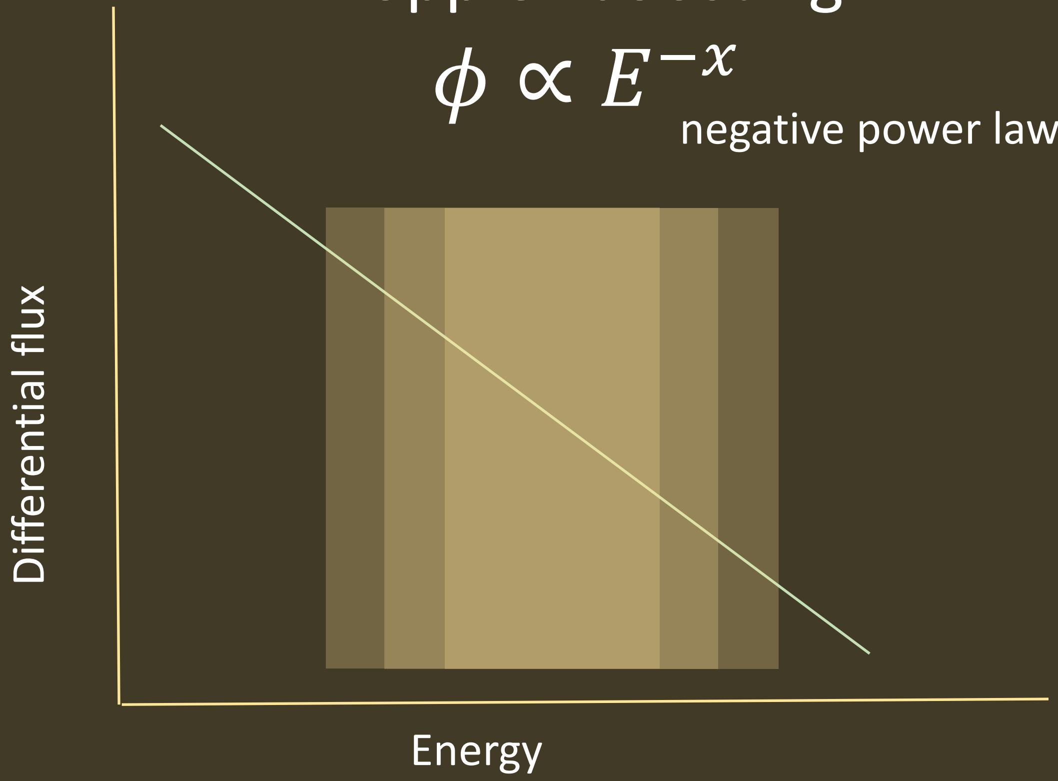
$$\tan\phi = \frac{\sin\theta}{\gamma * cos\theta - \frac{v}{c}}$$

+

Doppler boosting

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

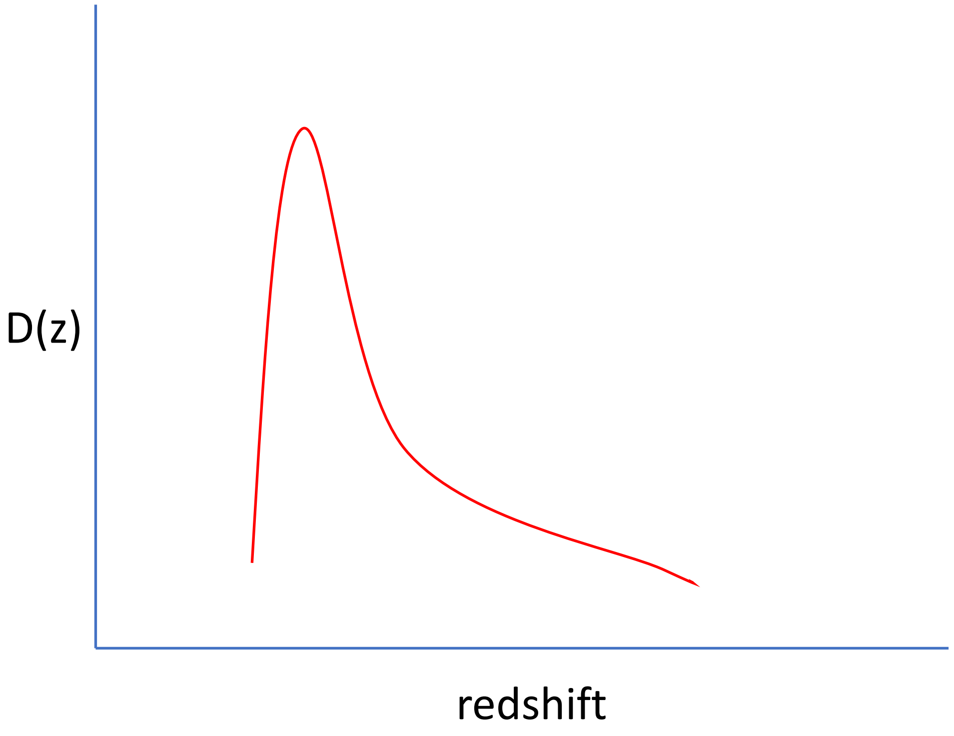
negative power law



Flux limited catalog -> more sources in direction of motion

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



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

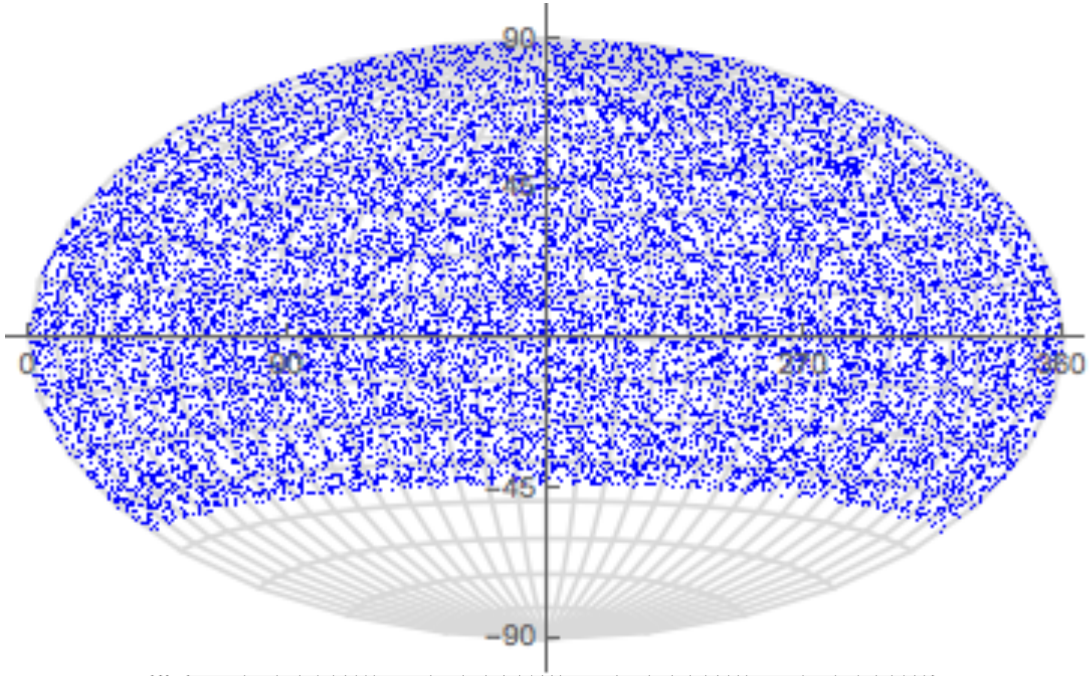
$\vec{\mathcal{K}} \rightarrow$ **The Kinematic dipole,** depends on source spectrum, source flux function, observer velocity

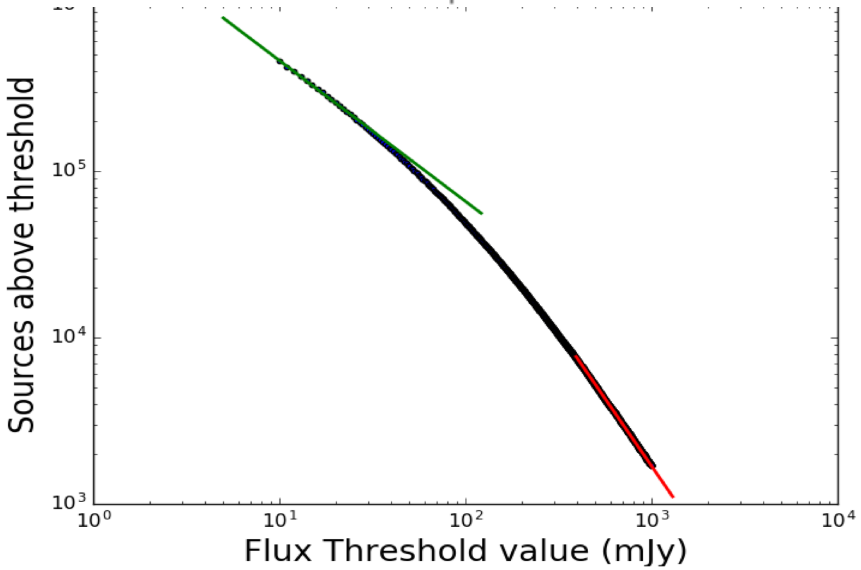
$\vec{\mathcal{R}} \rightarrow$ **The shot noise dipole,** $\propto 1/\sqrt{N}$, isotropic

$\vec{\mathcal{S}} \rightarrow$ **The clustering dipole,** local anisotropy due to growing structure

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

The NRAO VLA Sky Survey (NVSS)



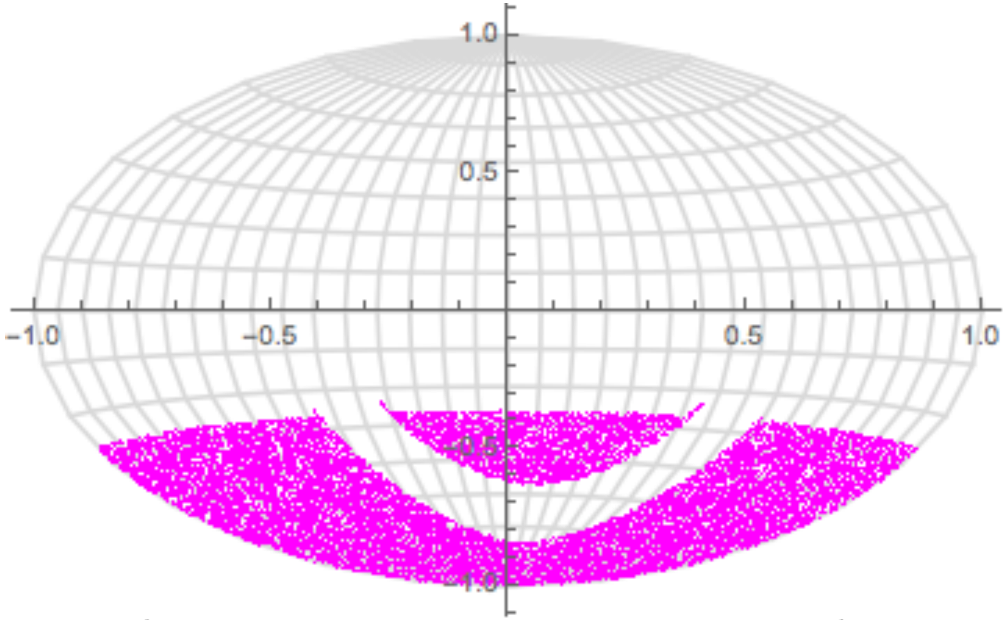


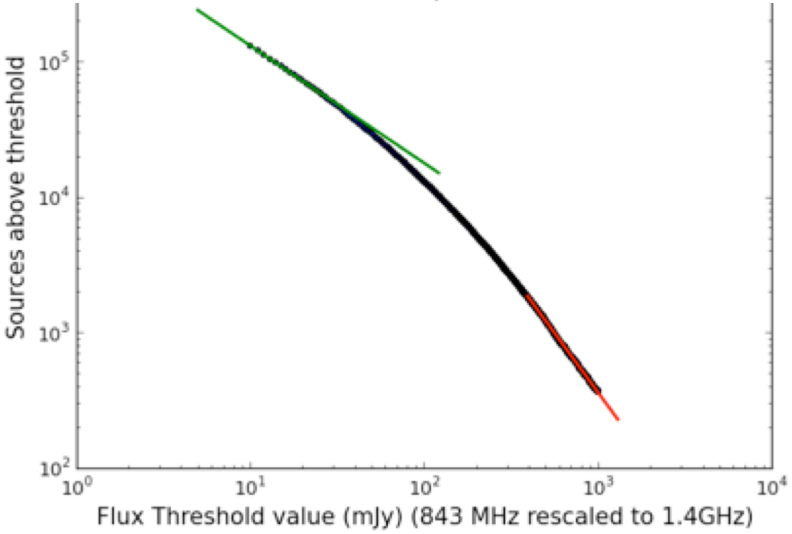
1.4 GHz survey of the Northern sky, by the National Radio Astronomy Observatory. Down to dec = -40.4°

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

Phys. Rev. D, 78, 043519

Sydney University Molonglo Sky Survey (SUMSS)

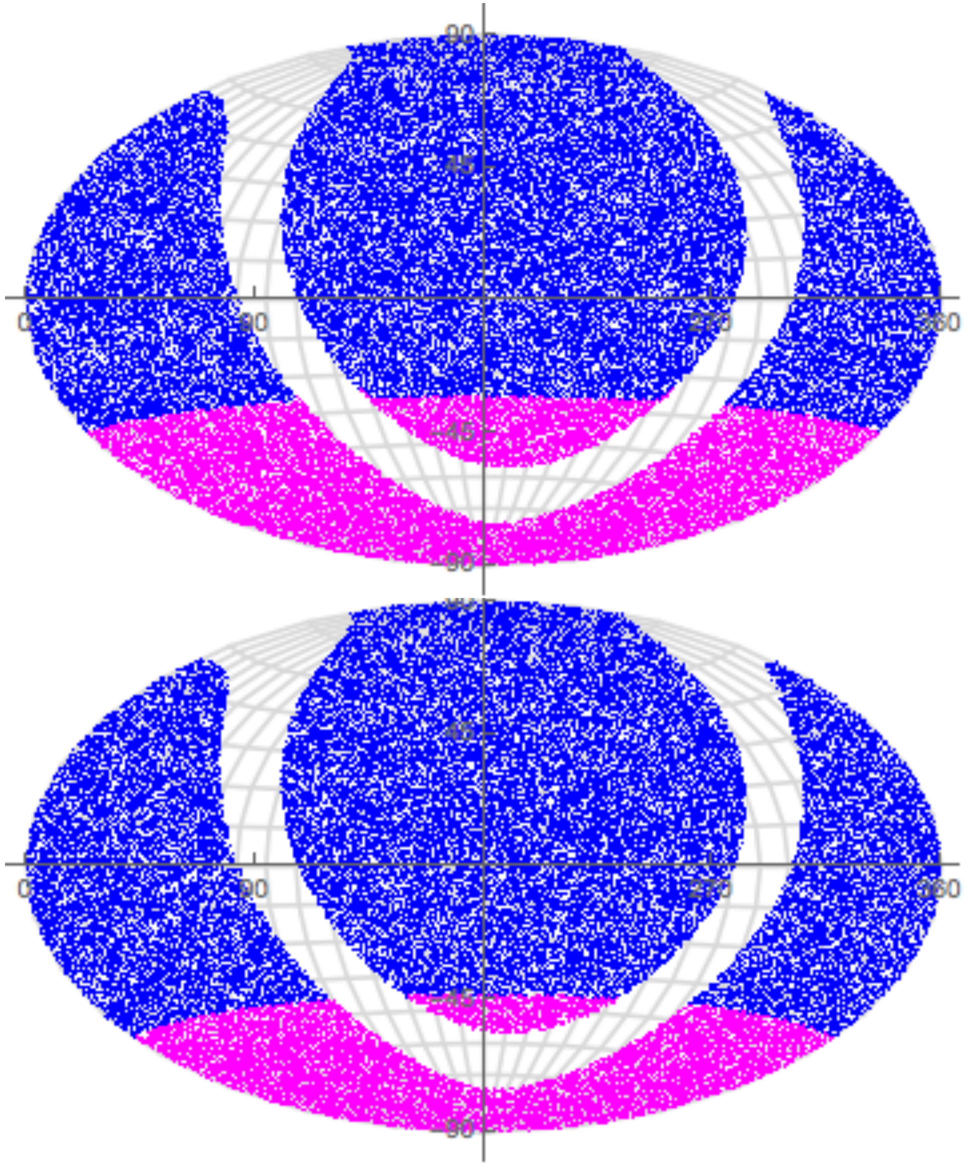




843 MHz survey of the Southern sky, by the Molonglo Observatory Synthesis telescope. Dec < -30.0°

211050 radio sources. Similar sensitivity and resolution to NVSS

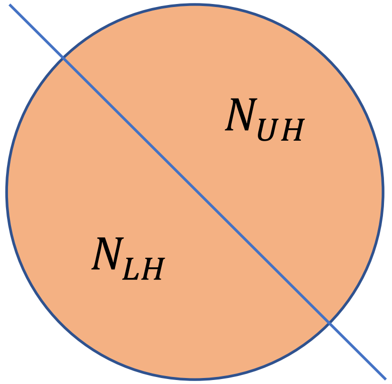
The NVSUMSS-Combined All Sky catalog



- 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, <120 sources at z<0.3 at 90%C.L.

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 $2.6/\sqrt{N}$

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

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

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

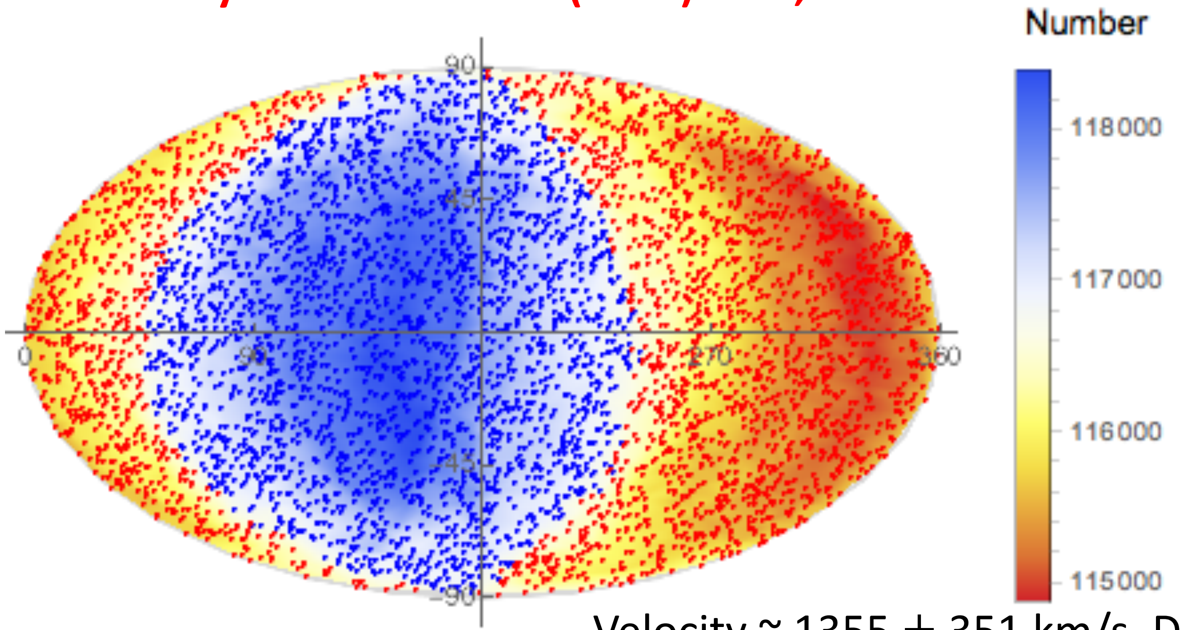
Relatively lower bias and statistical error $1/\sqrt{N}$

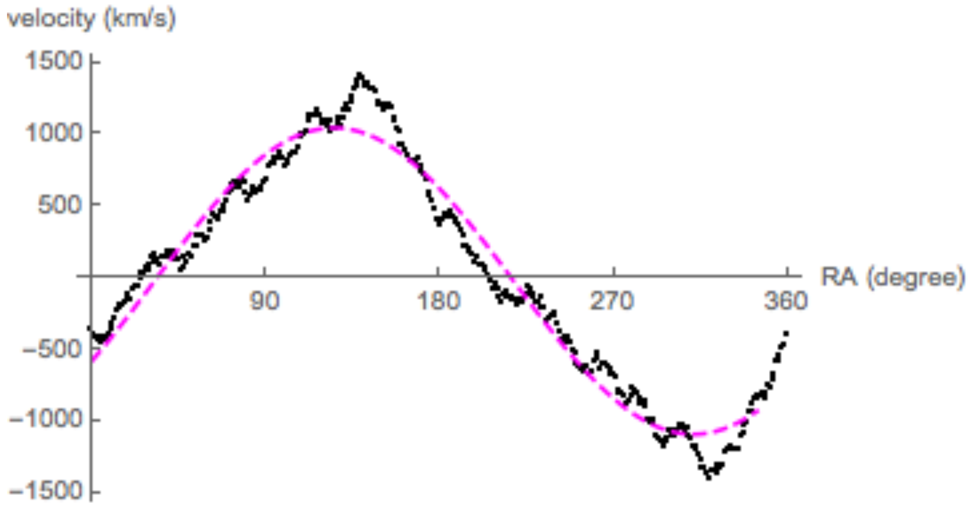
Rubart and Schwarz 2013

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

Results

Mon.Not.Roy.Astron.Soc. 471 (2017) no.1, 1045-1055





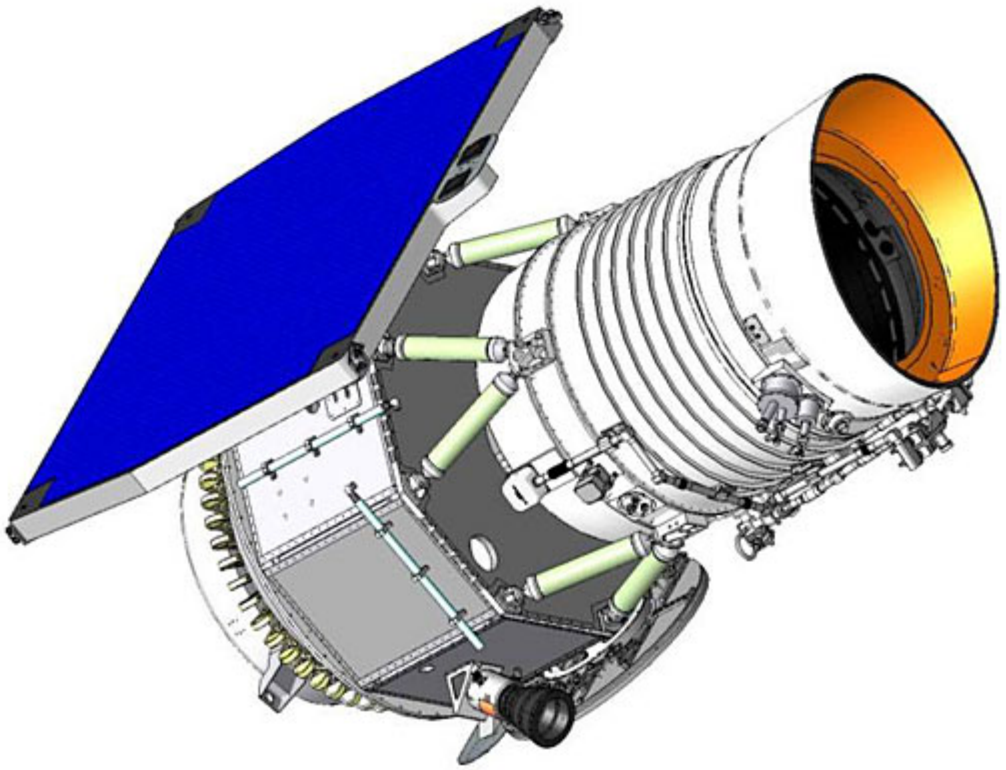
Velocity ~ 1355 $\pm$ 351 km/s, Dir within 10° of CMB dipole direction.

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

Bengaly et al 2018 JCAP 1804 (2018) no.04, 031 find a 5.1 sigma dipole in TGNSS

SKA phase 1 measurement ~10%
Bengaly (et al) 2018 : 1810.04960v1

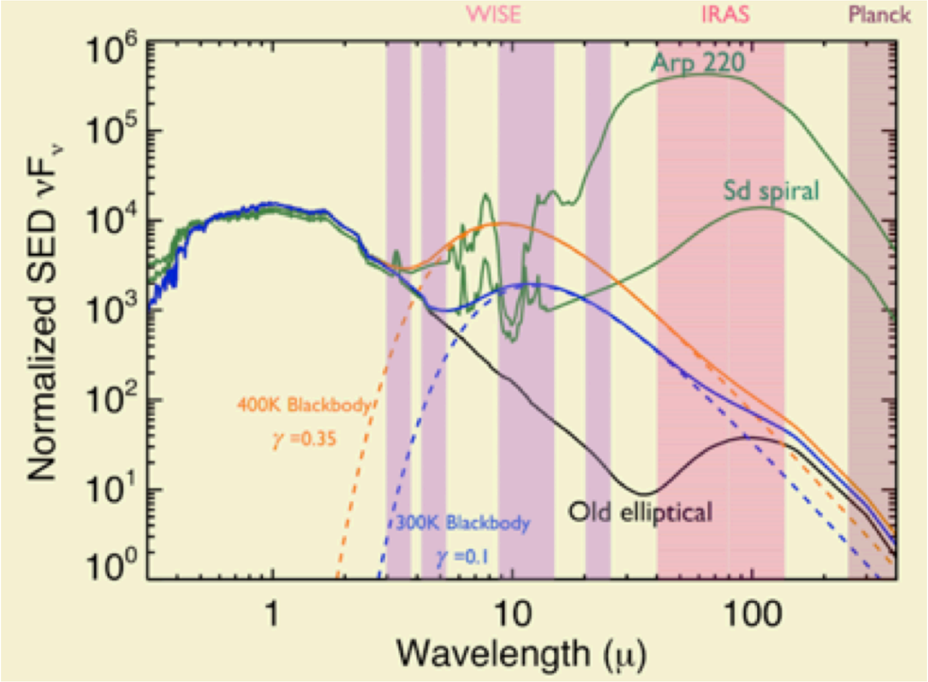
The Widefield Infrared Survey Explorer



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.

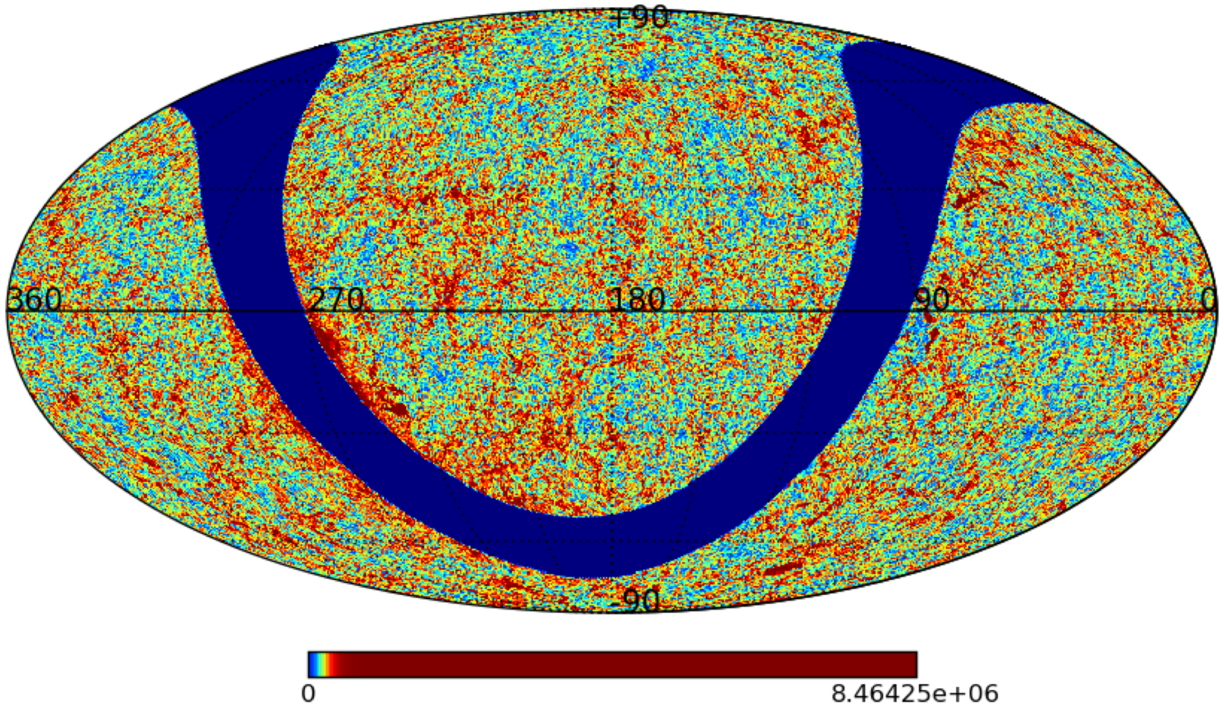
Directionally unbiased survey strategy, arc second angular resolution, multi band photometry.



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

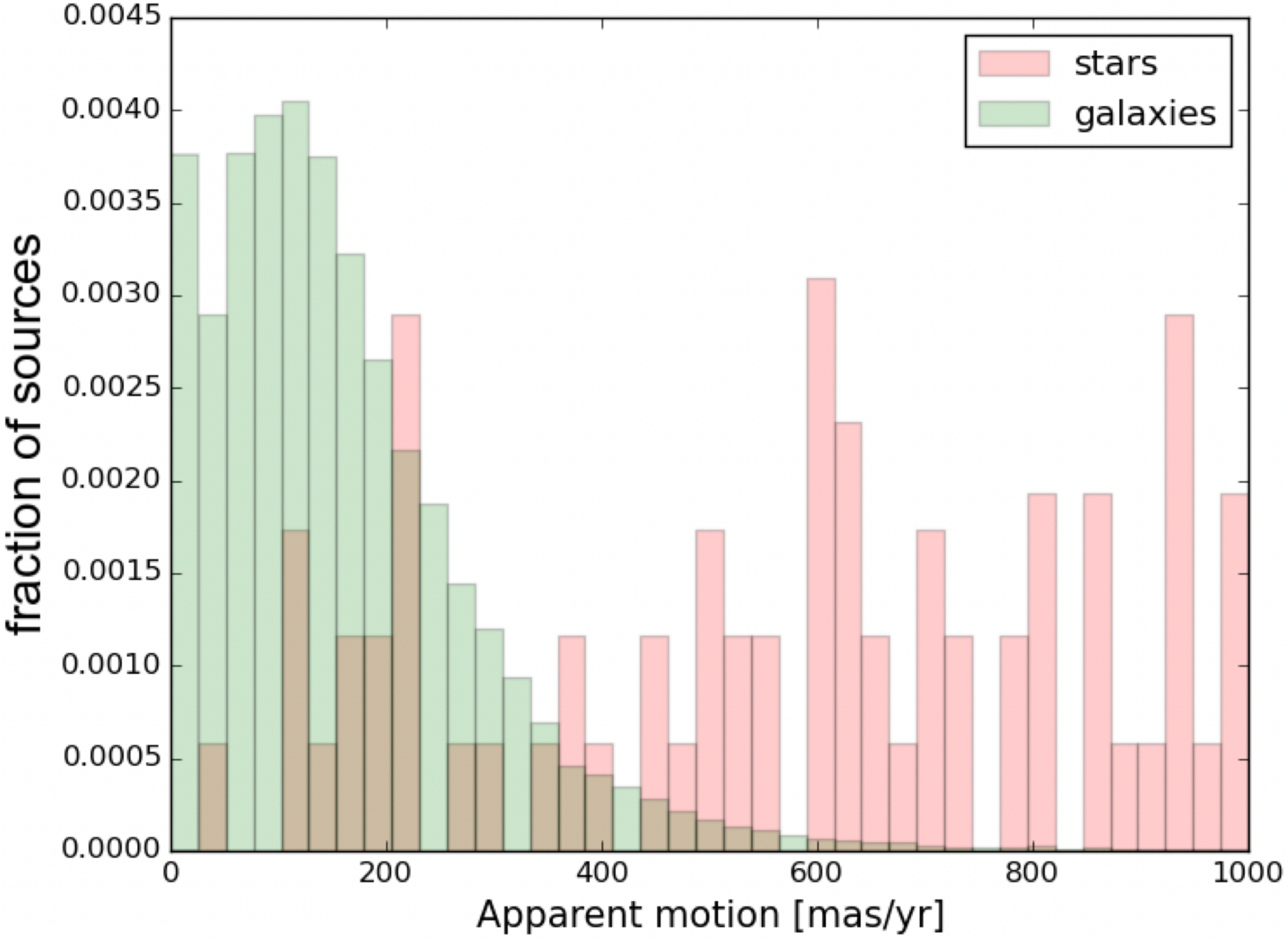
110 degrees from the CMB direction

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

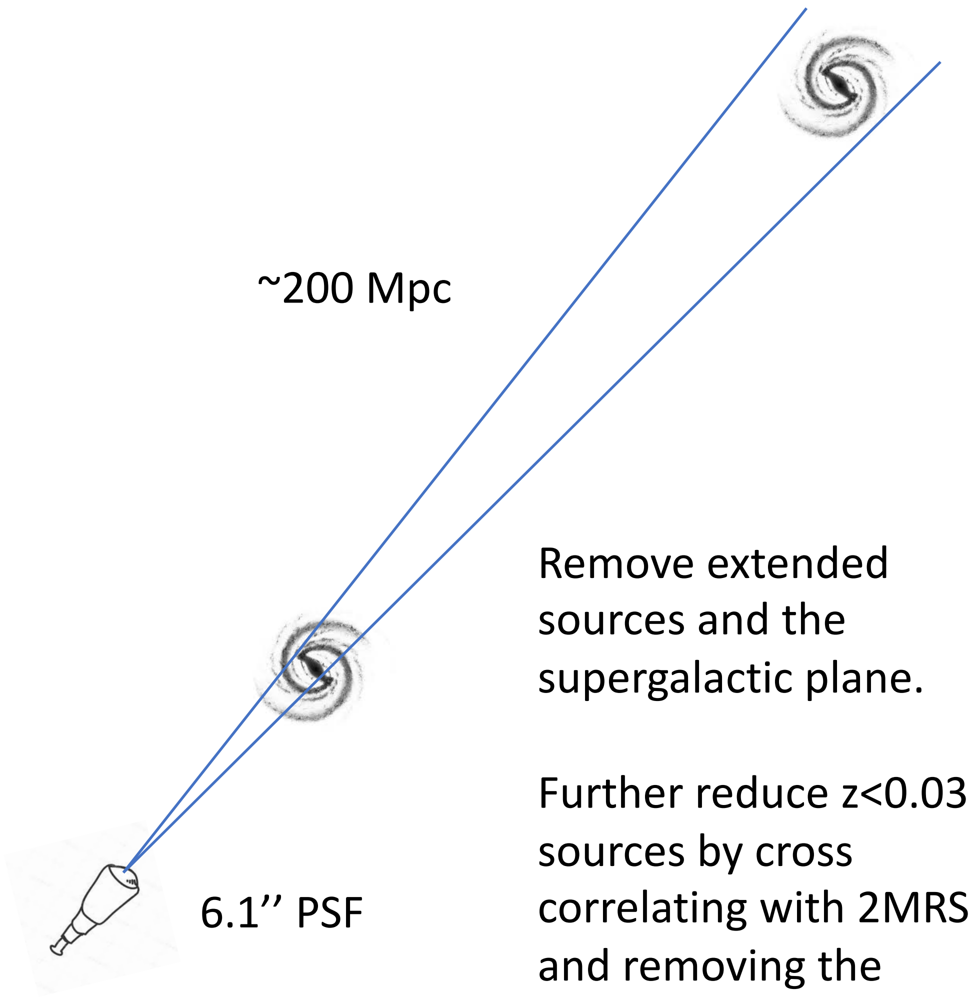
Cuts on apparent motion can bring star contamination down to 0.1%, while still keeping ~1.8 millin galaxies.

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

Dipole magnitude reduces to 0.014

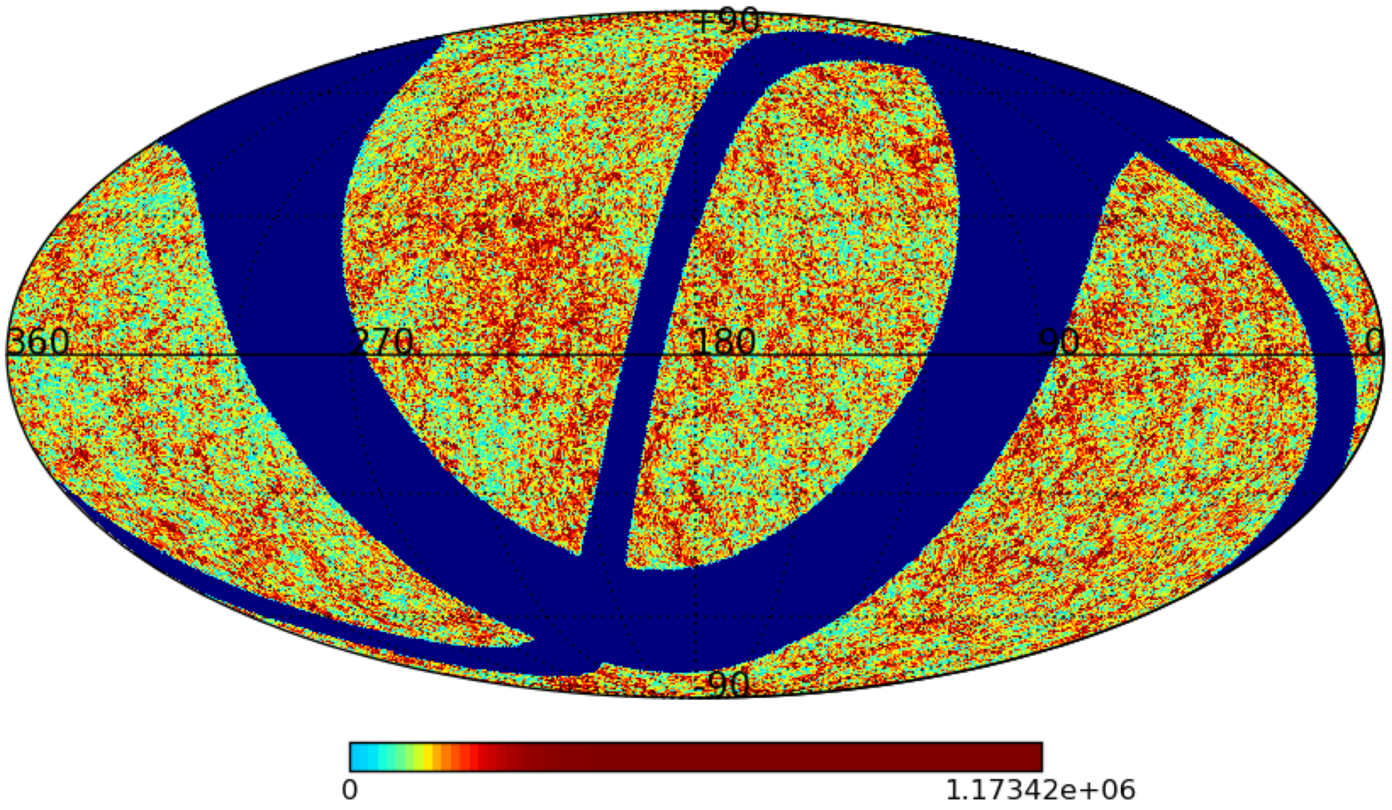
Star galaxy identification by cross correlating with SDSS

Suppressing local anisotropies



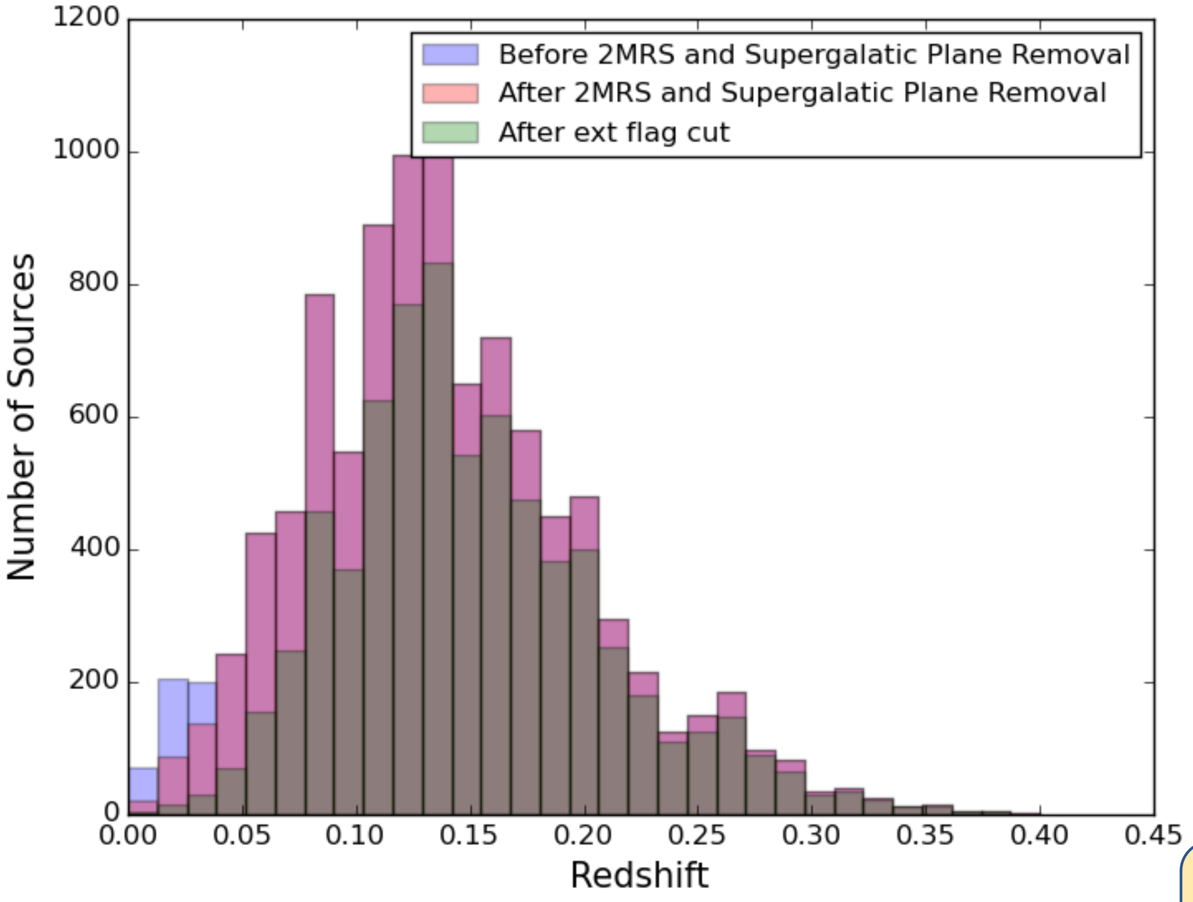
Remove extended sources and the supergalactic plane.

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



Result

Mon.Not.Roy.Astron.Soc. 477 (2018) no.2, 1772-1781

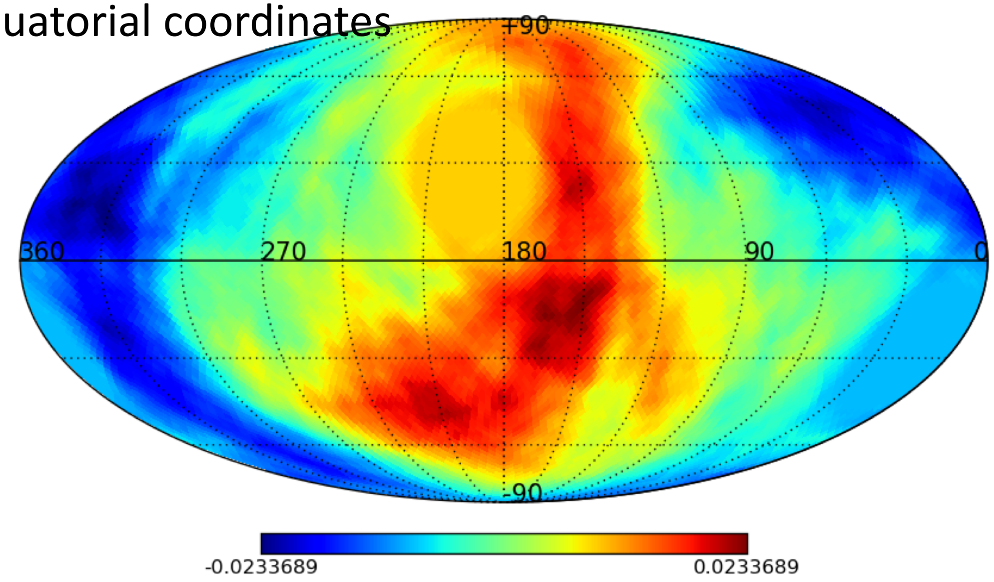


d = 0.0124 > 3600 km/s if fully kinematic

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

Total dipole is at least 4.6σ statistically significant.

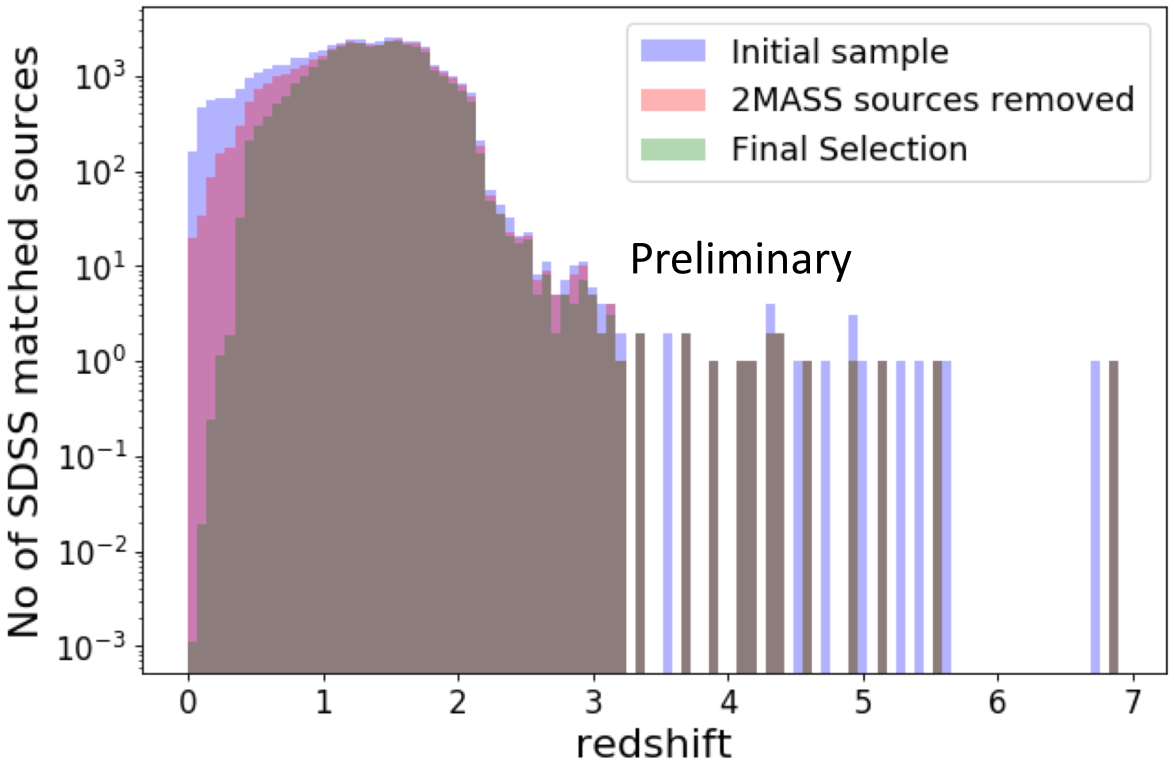
Equatorial coordinates

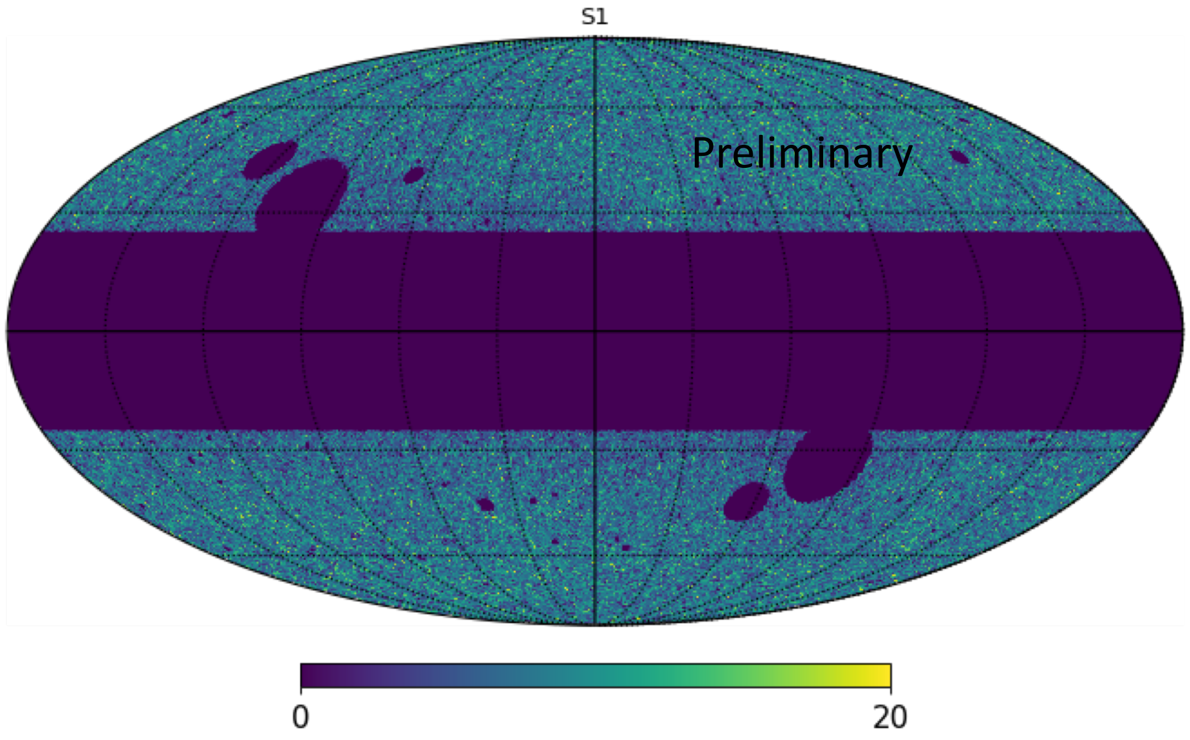


By cross correlating with Galaxy and Mass Assembly

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

WISE Quasars ~ 800000 sources

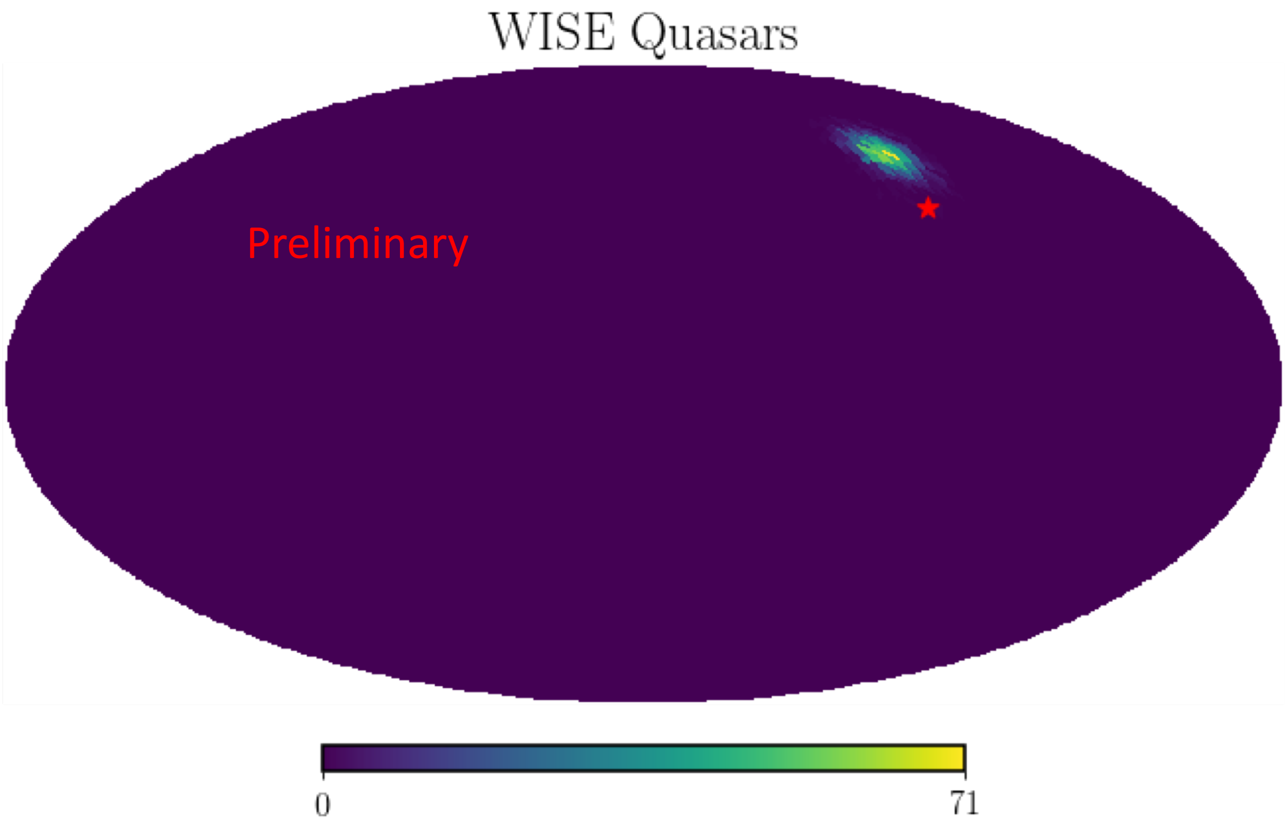


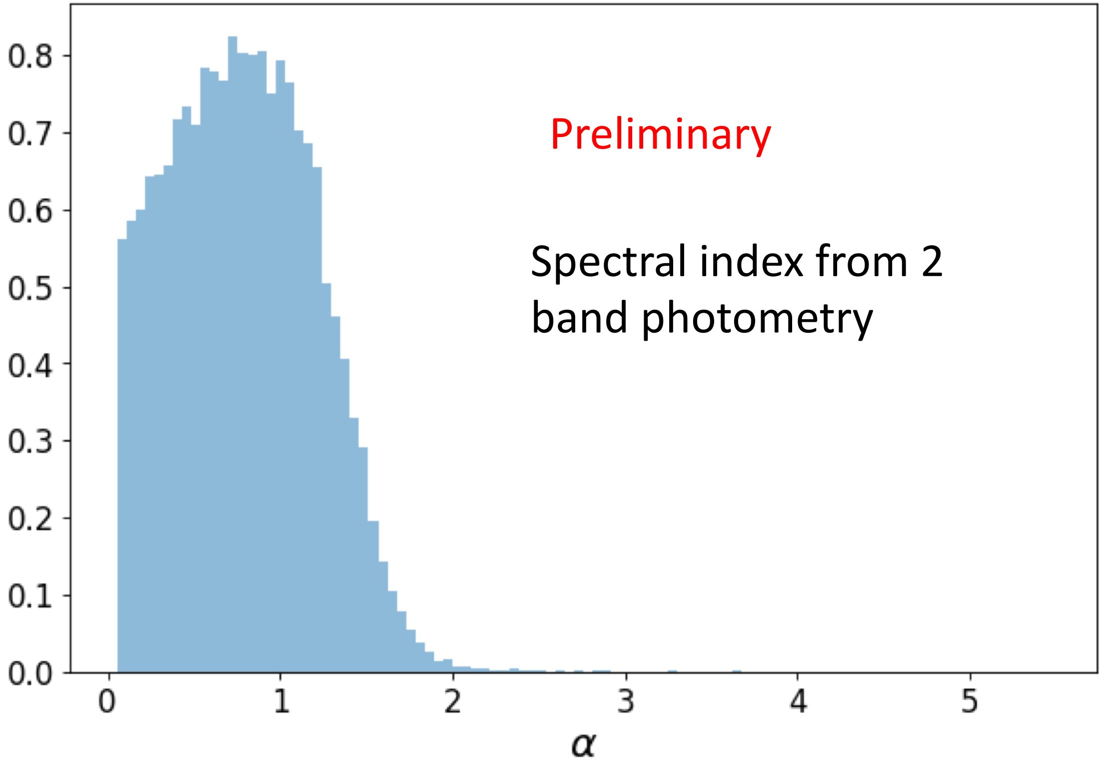


With N.Secrest and S.von Hausegger

In preparation

Robustly (>2 sigma) 16 degrees away from the CMB dipole

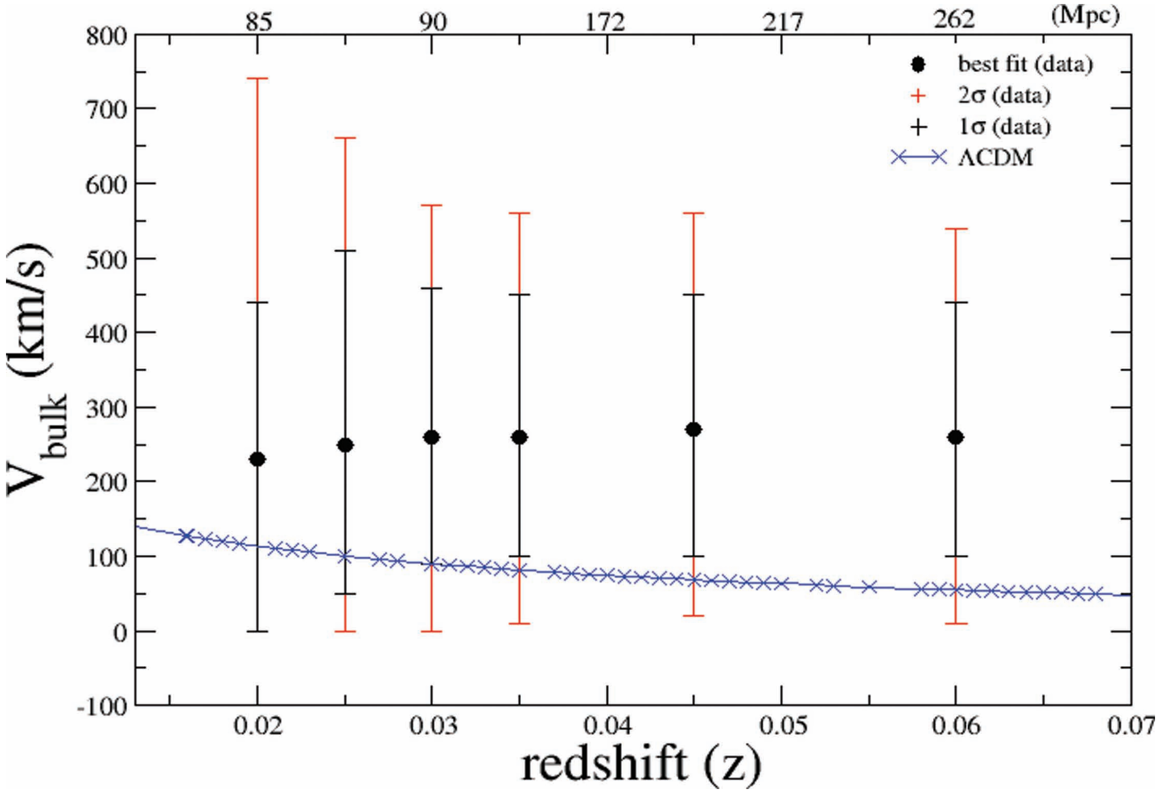


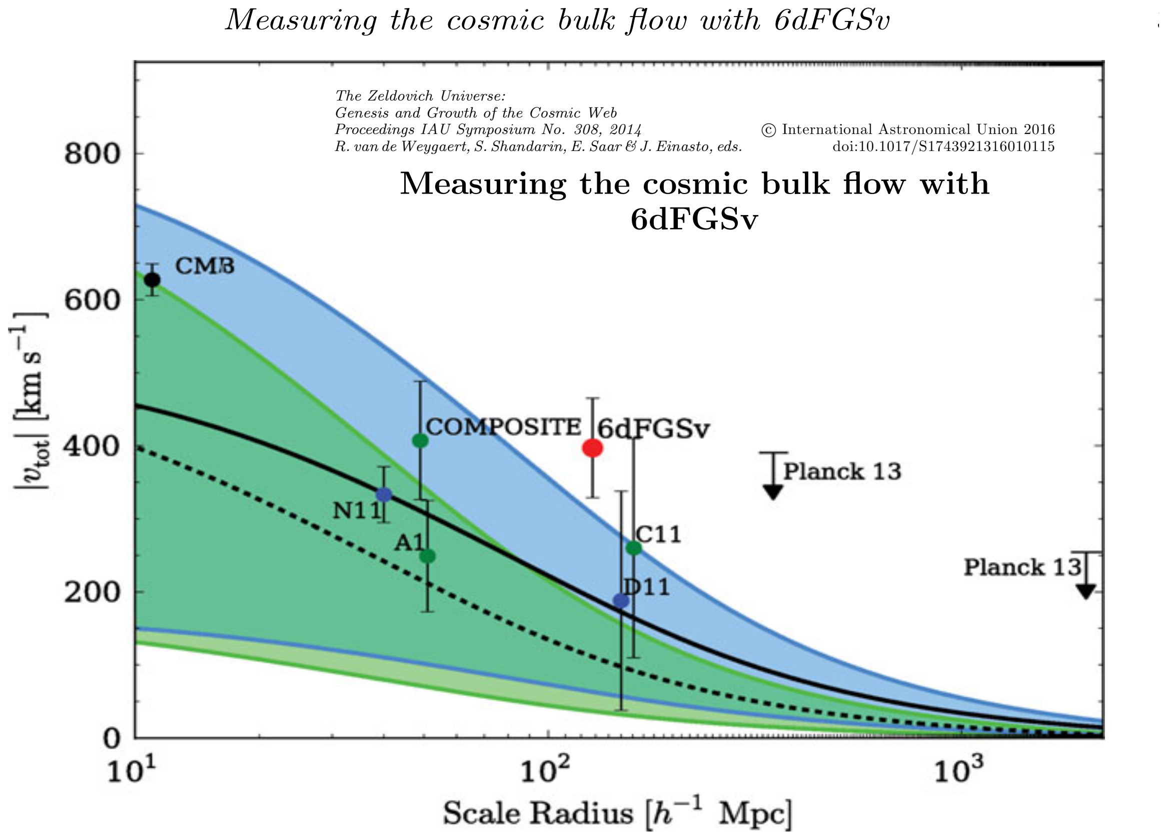


V = ~1400 km s^-1, 3.4 sigma from Kinematic interpretation of the CMB dipole

These are all just dipoles in number counts. The velocity is an interpretation.
But 'something is happening in that direction'

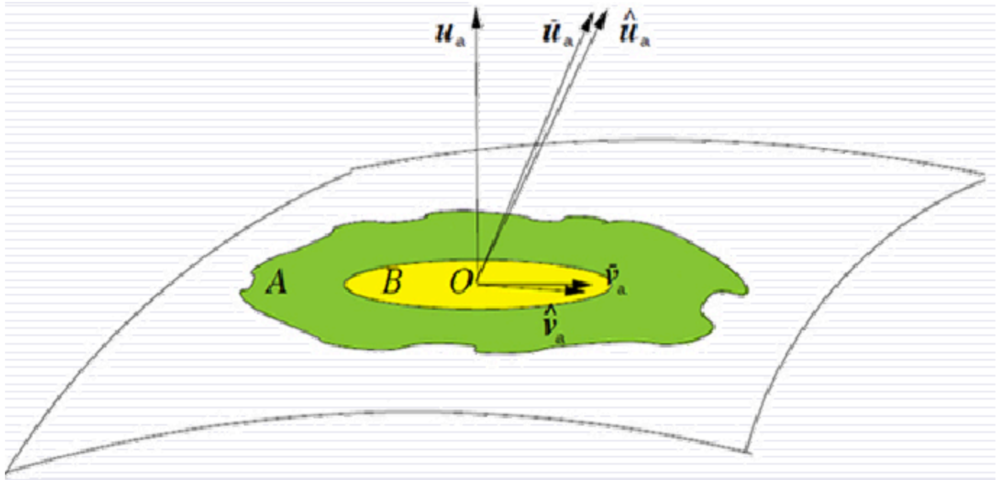
Where is the cosmic 'rest frame'?





Colin J., Mohayaee R., Sarkar S. & Shafieloo A., 2011, MNRAS, 414, 264
Also density field reconstructions: Carrick et al 2015

The tilted Friedmann Universe



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

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

… if so there should be a dipole asymmetry in the inferred deceleration parameter in the same direction – i.e. towards the CMB dipole

The patch A has mean peculiar velocity $\tilde{v}_a$ with $\vartheta = \tilde{\mathrm{D}}^a v_a \gtrless 0$ and $\dot{\vartheta} \gtrless 0$
(the sign depending on whether the bulk flow is accelerating or decelerating)

Inside region B, the r.h.s. of the expression

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

drops below 1 and the observer 'measures' *negative* deceleration parameter in one direction of the sky

The deceleration parameter is expected to pick up a scale dependent dipolar modulation

Test this with a sample of 740 Type 1a Supernovae

$q = q_m + q_d e^{-z/S}$ Maximum Likelihood Estimator of Nielsen et al 2015, Joint Lightcurve Analysis Dataset
Use Heliocentric observables.

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
Tilted universe	−208.28	−0.157	−8.03	0.0262	−0.489	0.135	0.0394	0.931	3.00	−0.01
No tilt ($q_{\rm d}=0$)	−189.52	−0.166	0	–	−0.460	0.133	0.0396	0.931	2.99	−0.0
No accn. ($q_{\rm m}=0$)	−205.98	0	−6.84	0.0384	−0.836	0.134	0.0365	0.931	2.99	−0.0

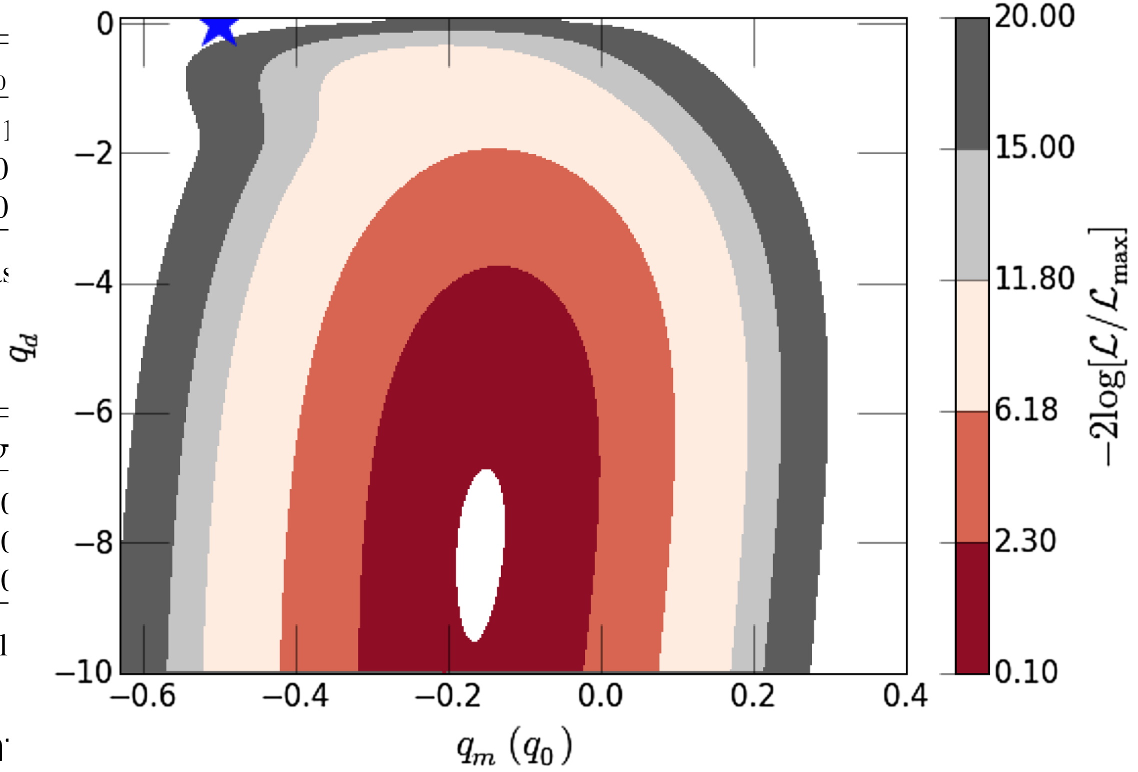
Notes. The BIC for the models above is −129.00, −123.45, and −133.31, providing strong evidence for the las

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
Tilted universe	−216.90	−0.154	−6.33	0.0305	−0.497	0.134	0.0395	0.932	3.04	−0.0158	0.(
No tilt ($q_{\rm d}=0$)	−203.23	−0.187	0	–	−0.425	0.133	0.0398	0.932	3.05	−0.0151	0.(
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.(

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

A&A 631, L13 (2019).



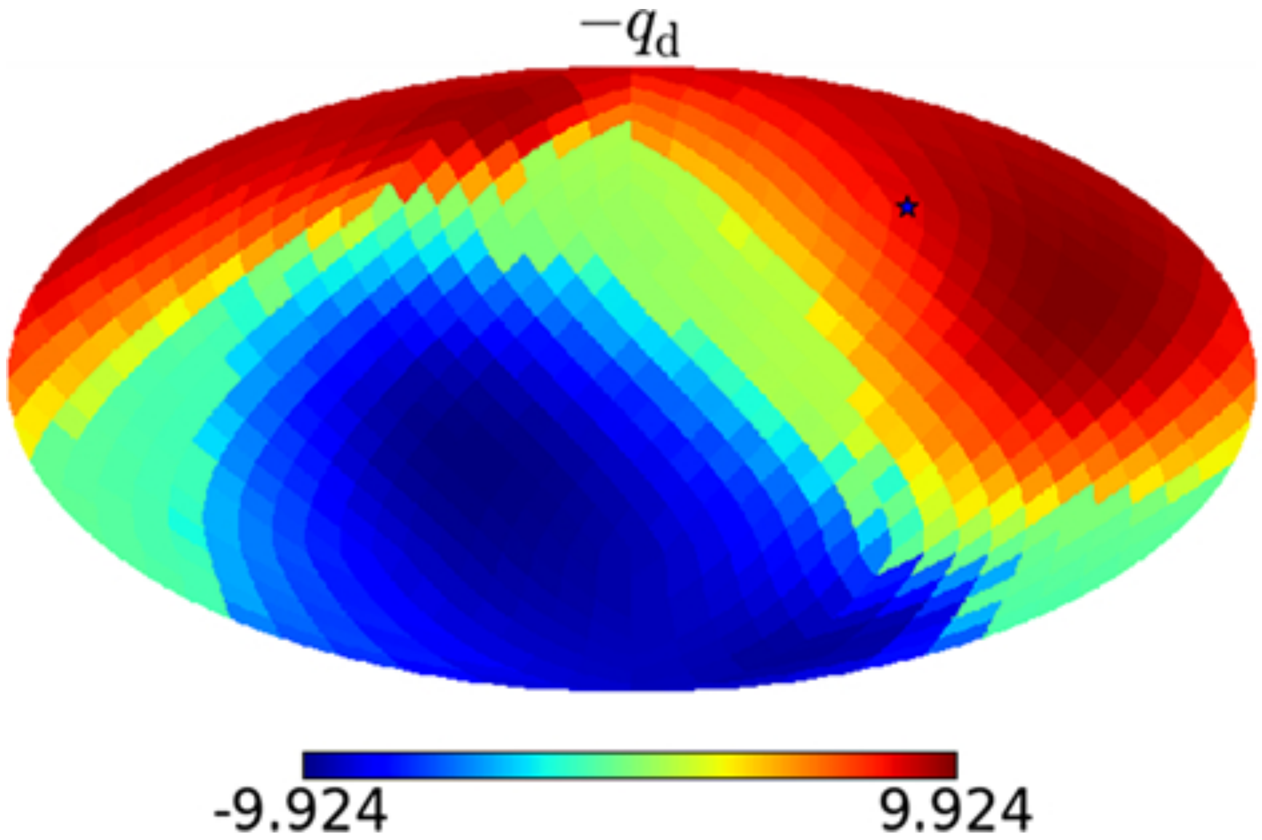
The dipolar component of q is larger than the monopole, and domina

$q_d >> q_m$

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’!

Vary the directions a posteriori



This result is:

In agreement with a covariant prediction by Christos Tsagas

Statistically significant at 3.4 σ level without making colour and stretch sample and redshift dependent

The dipole is closely aligned to the CMB dipole

Fits a lower $\sigma_{M,0} = 0.106$, ~20% less than in any supernova cosmology analysis

Redshift and sample dependent treatment of colour and stretch increases the statistical significance of the dipole to >4.6 sigma

$|q_{dip}| \gg q_m$ (all the way to z~0.1)

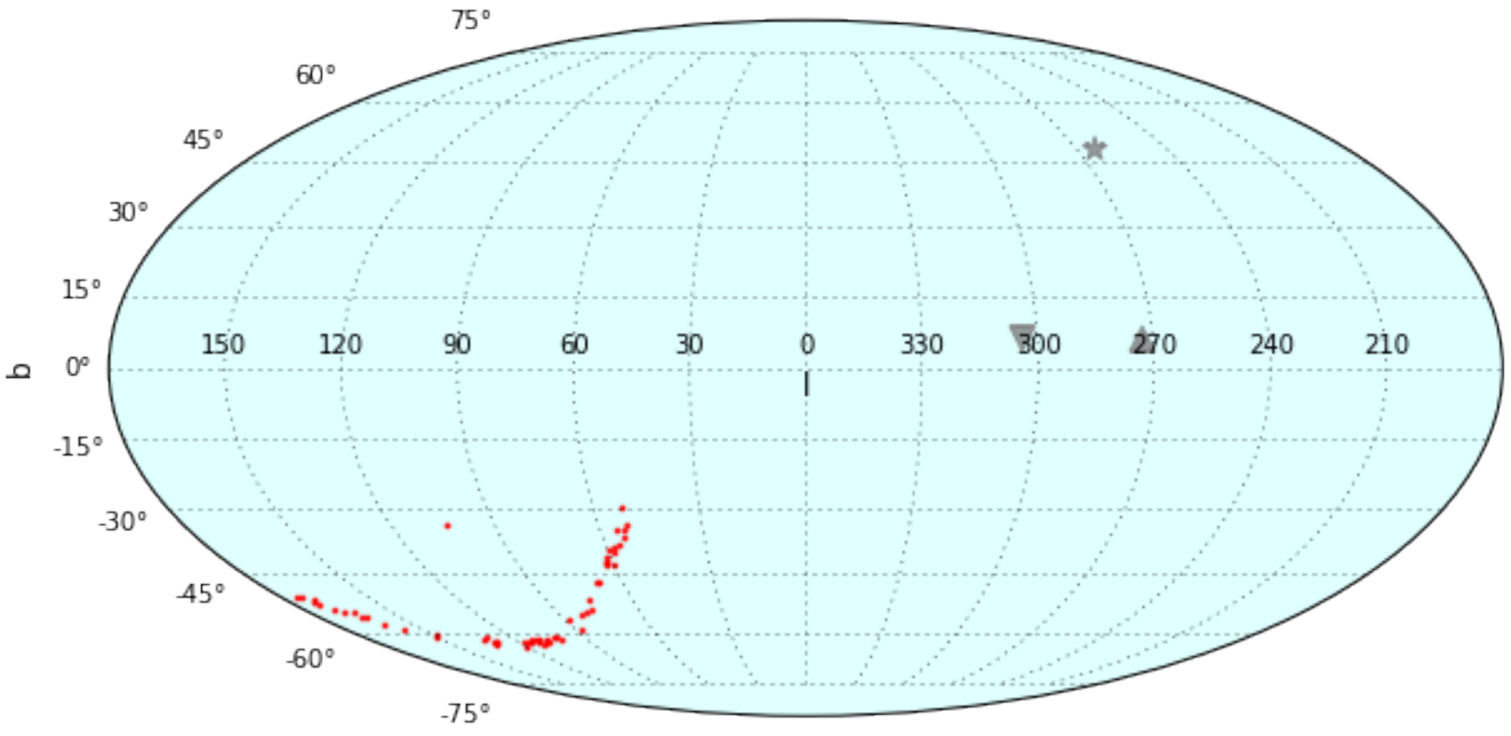
A posteriori test, varying directions : just 23 degrees away from the CMB dipole. Likelihood improves by just ~3

We have found a tilt in the local Universe!

A.R. King and G.F.R. Ellis

Tilted Homogenous Cosmological Models?

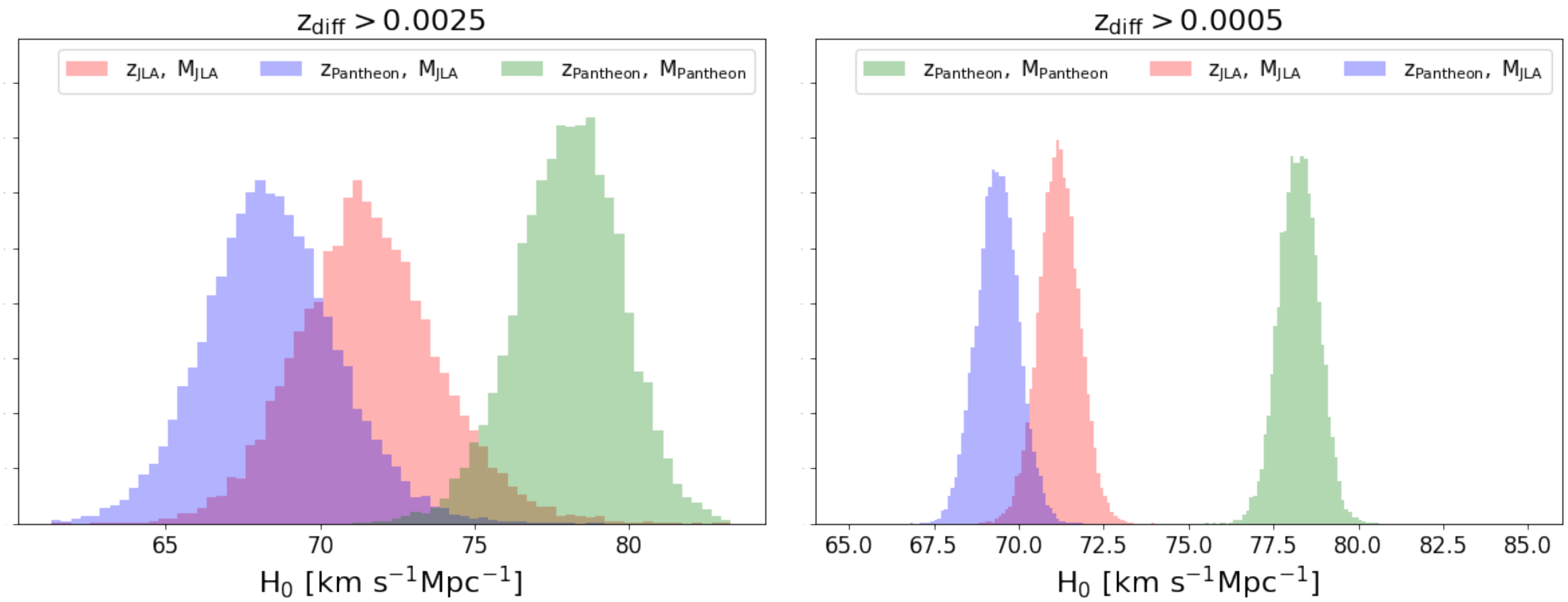
Discrepancies between 2 SN1a datasets



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

1905.00221

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

Conclusions

- Number counts of flux limited catalogues in radio and infrared all indicate mild (1.5σ) to slightly significant ($\sim 3.4\sigma$) tensions with the kinematic interpretation of the CMB dipole
  - Similar tensions reported between 3 and 5 sigma in other radio galaxy catalogues as well as X-ray clusters etc. Migkas et al.
- The end of the bulk flow of the local Universe has not been found.
  - Where is the cosmic rest frame?
- Evidence $> 3.4\sigma$ for a tilt in the local Universe. Isotropic acceleration compatible with 0 at < 1.4 sigma

The ‘fitting problem’ in cosmology

The most correct paper ever written that is relevant to observational cosmology (IMO)

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.

Offers no real solutions. Just discusses them.

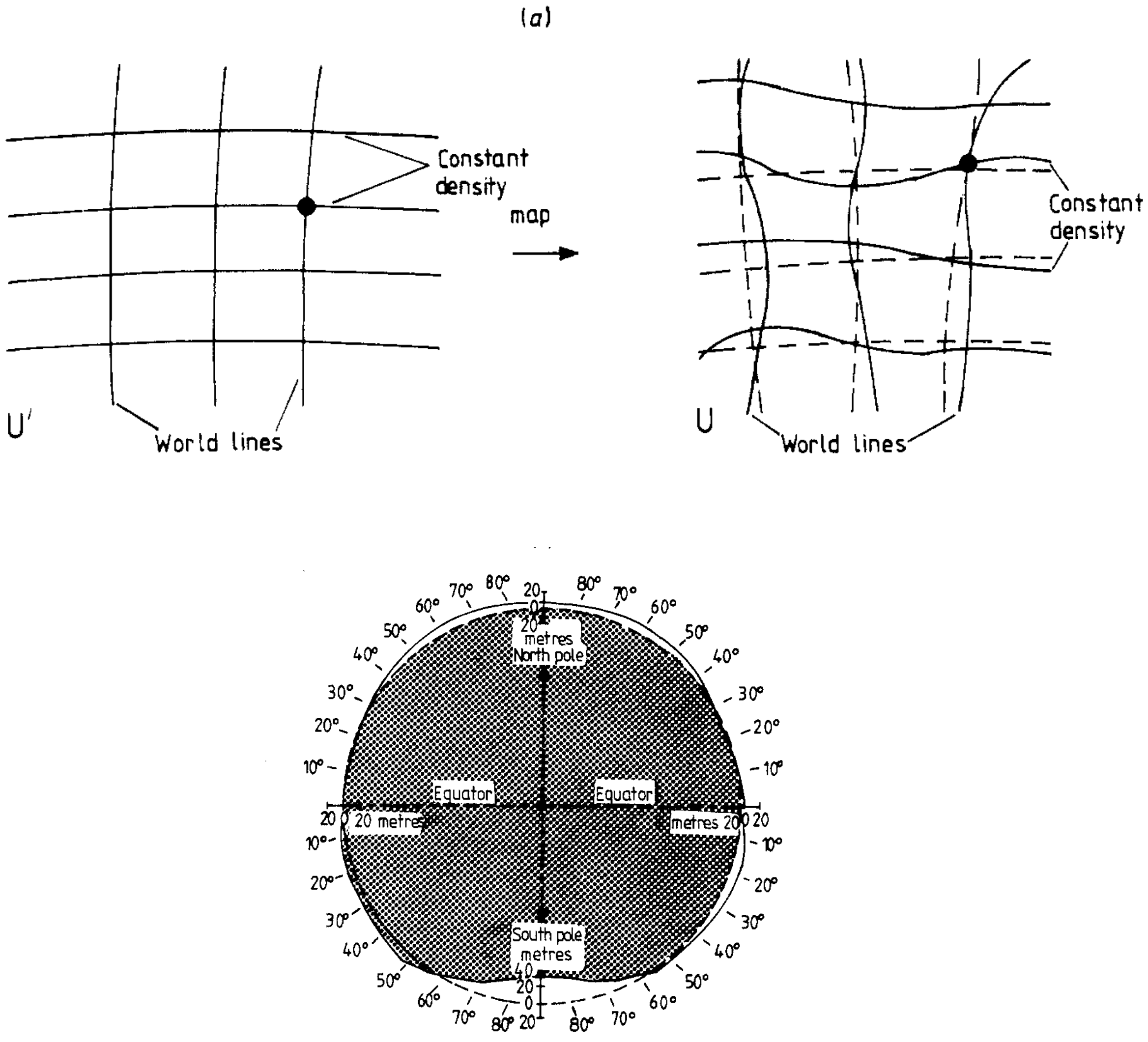


Figure 1. (*a*) An exactly uniform and spherically symmetrical FLRW universe U′ mapped into the lumpy universe U so as to give the best fit possible. (*b*) An exactly spherical sphere fitted to the lumpy world to give the best fit possible.

The FLRW Universe in Kinematics

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

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

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

Matt Visser 2004

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.

	$-2\log\mathcal{L}_{\max}$	$q_{\rm m}$	$q_{\rm d}$	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

$q_d >> q_m$

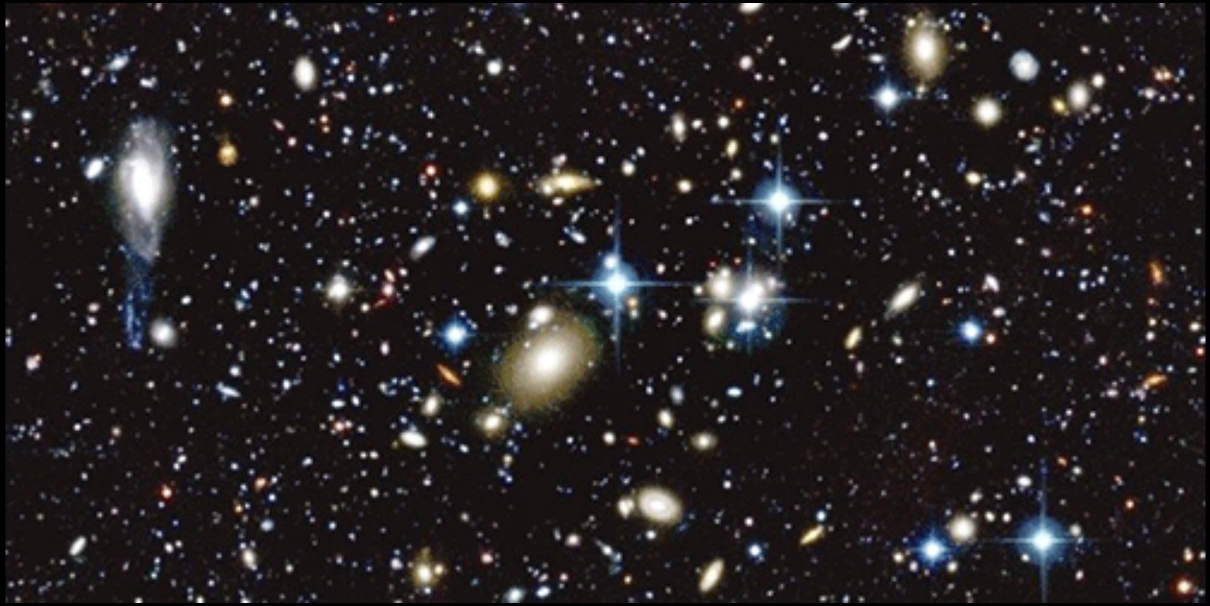
The significance of q_o being negative is $<1.4\sigma$!

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

But the real Universe has structure on all scales

The FLRW universe

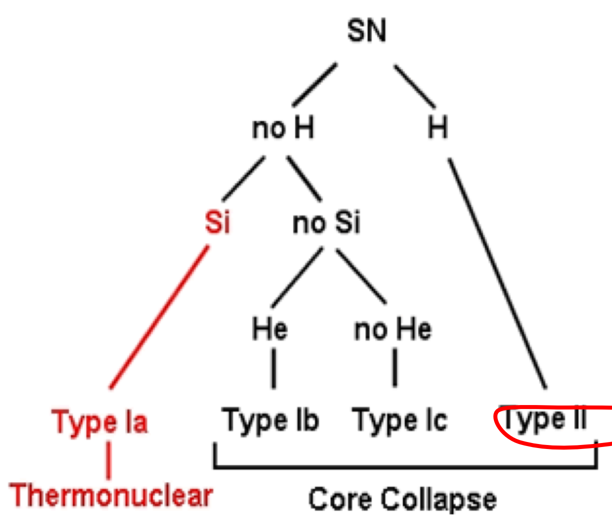
The Real Universe

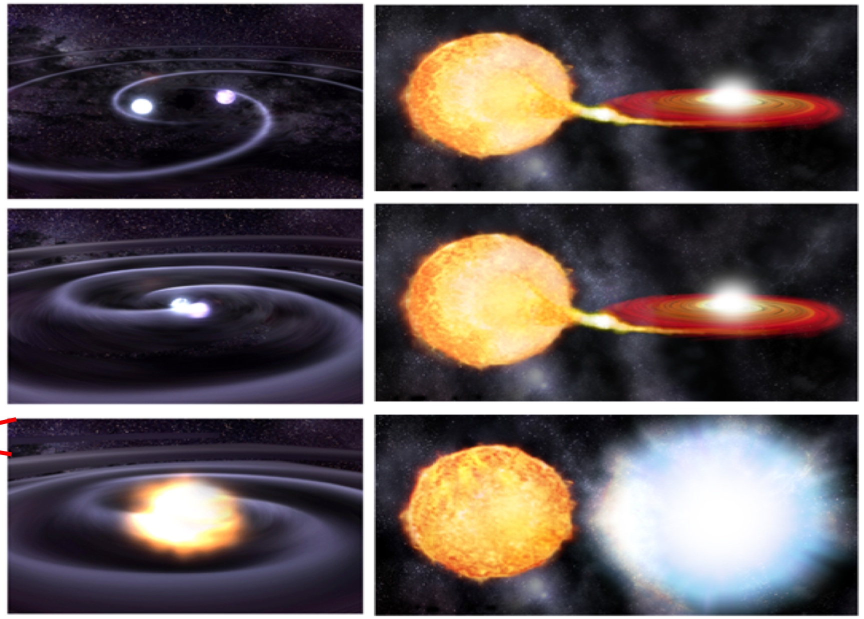


How does the real Universe evolve?

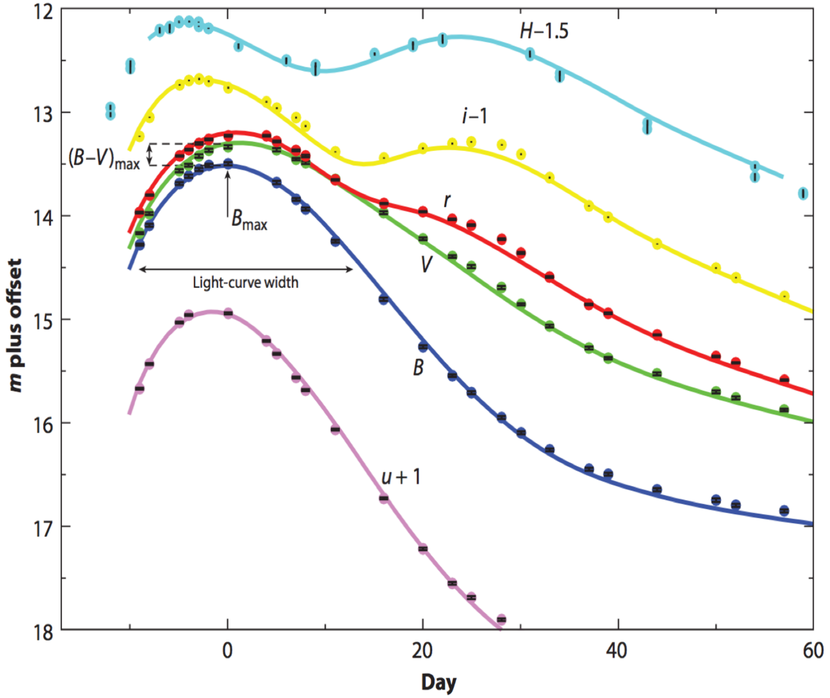
What are Type Ia supernovae?

Goobar & Leibundgut, arXiv:1102.1431

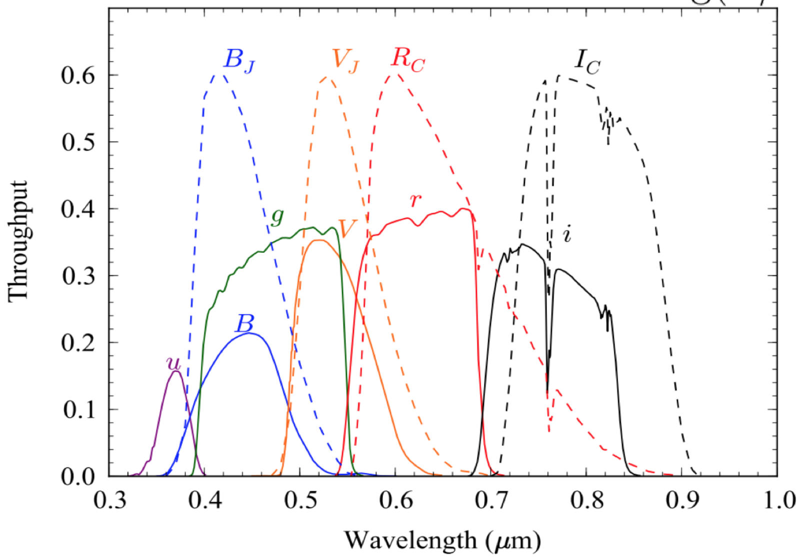




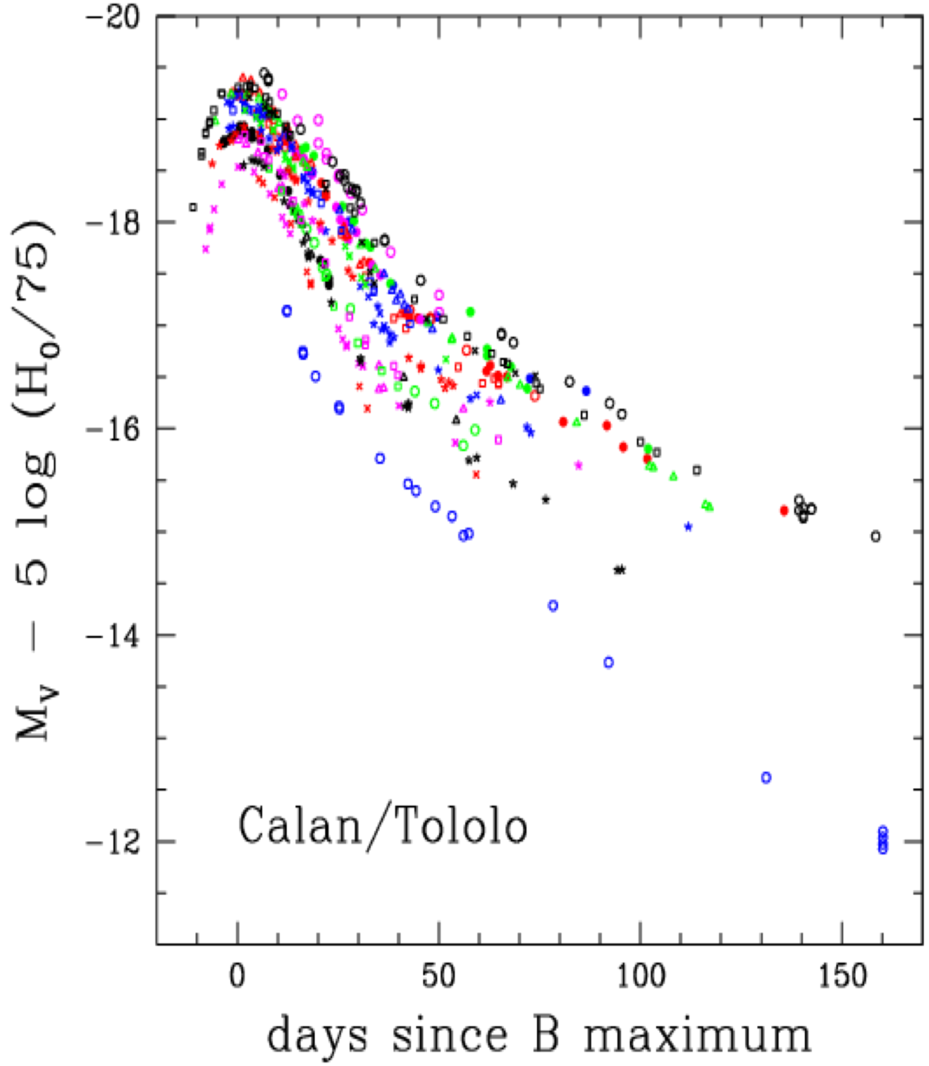
A white dwarf accreting matter from a binary companion, reignites when crossing ~1.44 Solar Masses



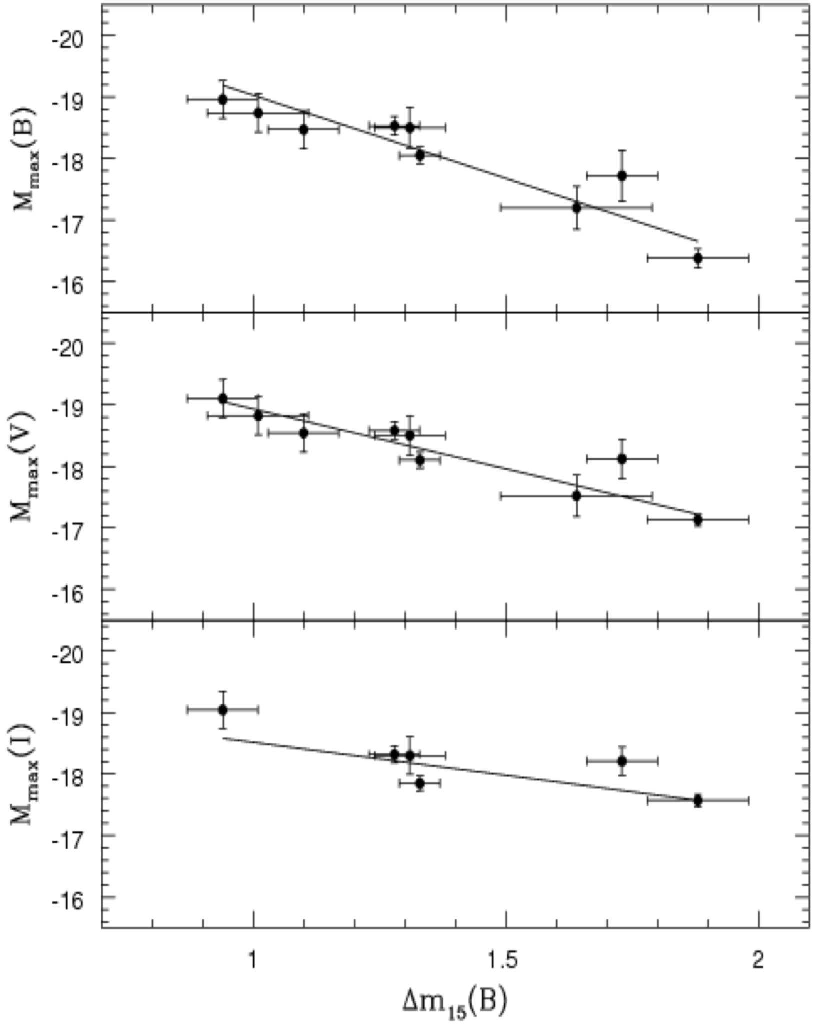
$$m = -2.5\log(F/F_{\rm ref})$$



They are certainly *not* ‘standard candles’



Hamuy, arXiv:311.5099

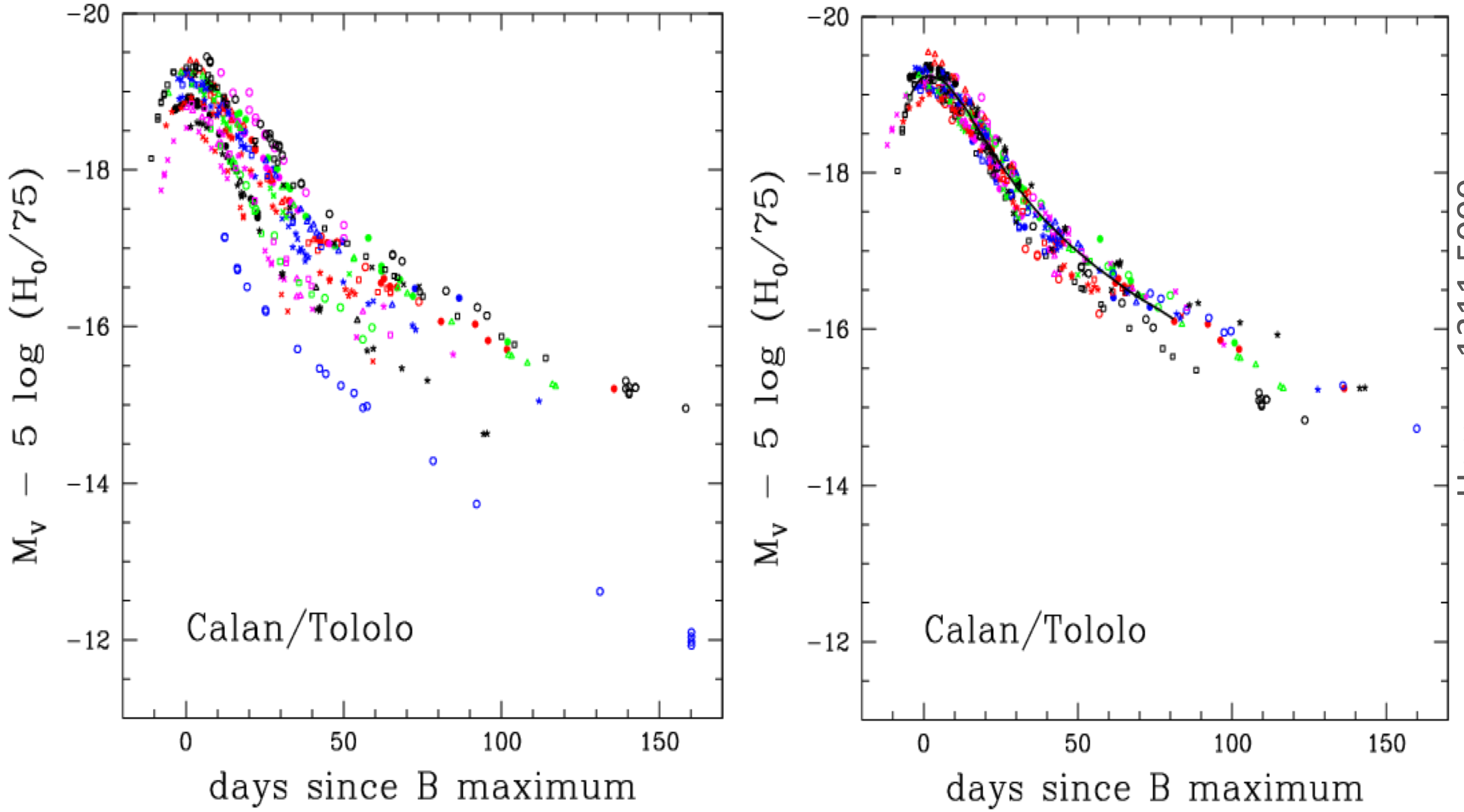


Phillips, ApJ **413**:L105, 1993

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



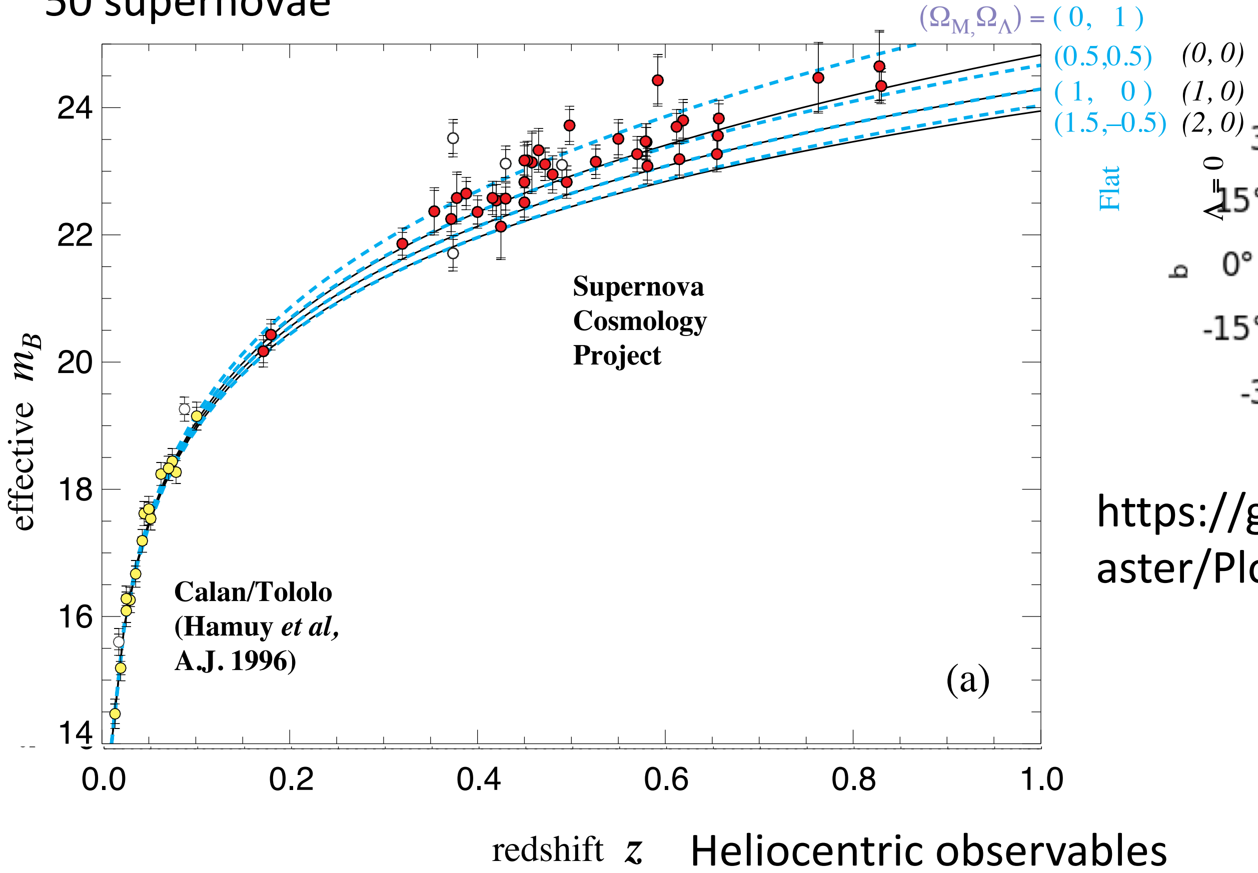
Hamuy, 1311.5099

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

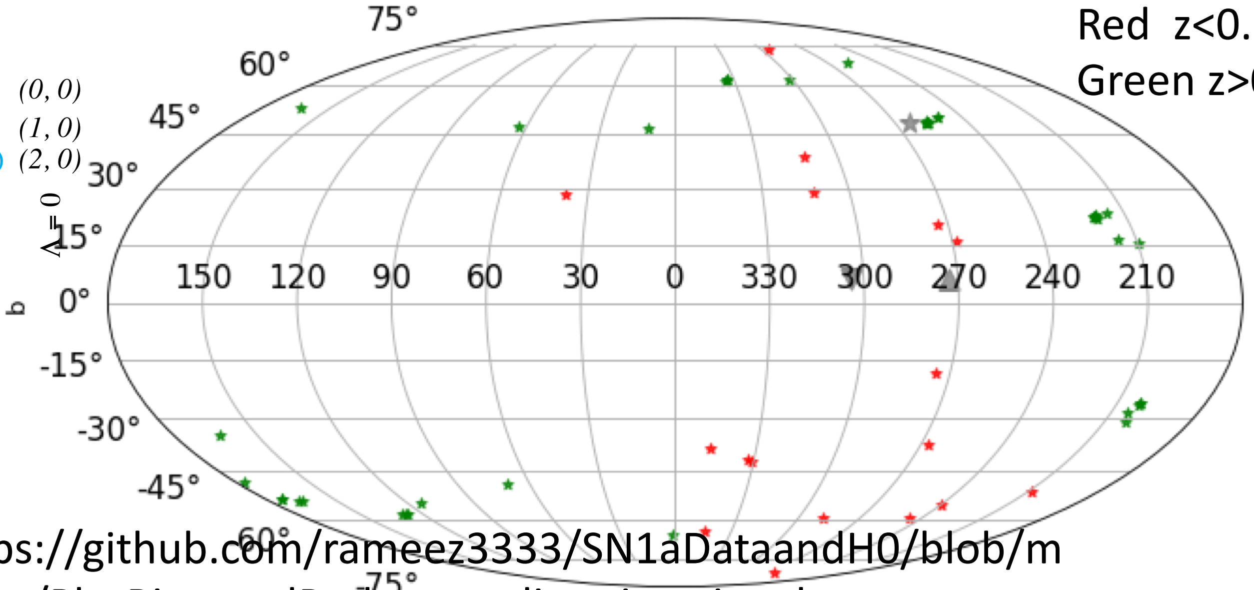
Use a standard template (e.g. SALT 2) to make 'stretch' and 'colour' corrections …

The fitting problem and supernova data, a history

~50 supernovae

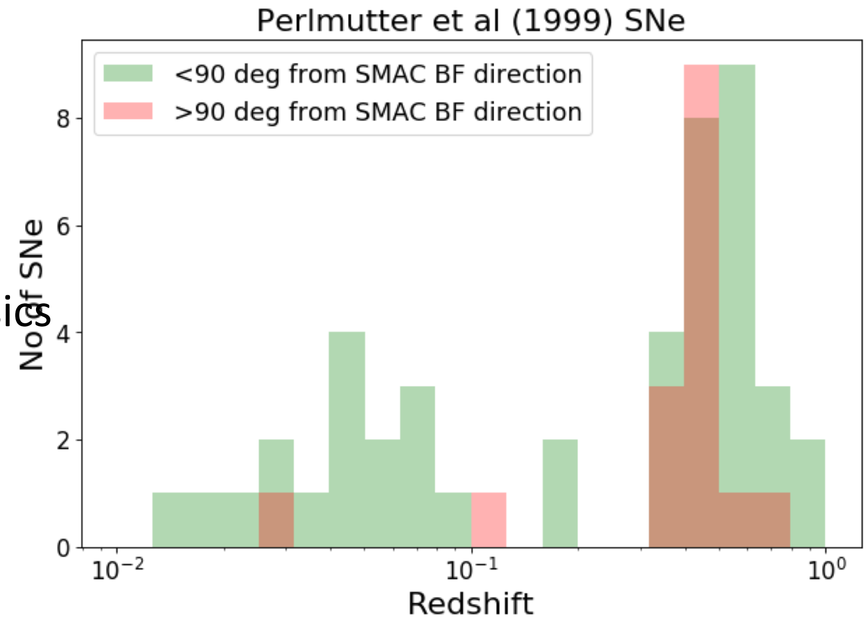


Heliocentric observables



Red z<0.1
Green z>0.1

https://github.com/rameez3333/SN1aDataandH0/blob/master/PlotRiessandPerlmutterdirections.ipynb



'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)'

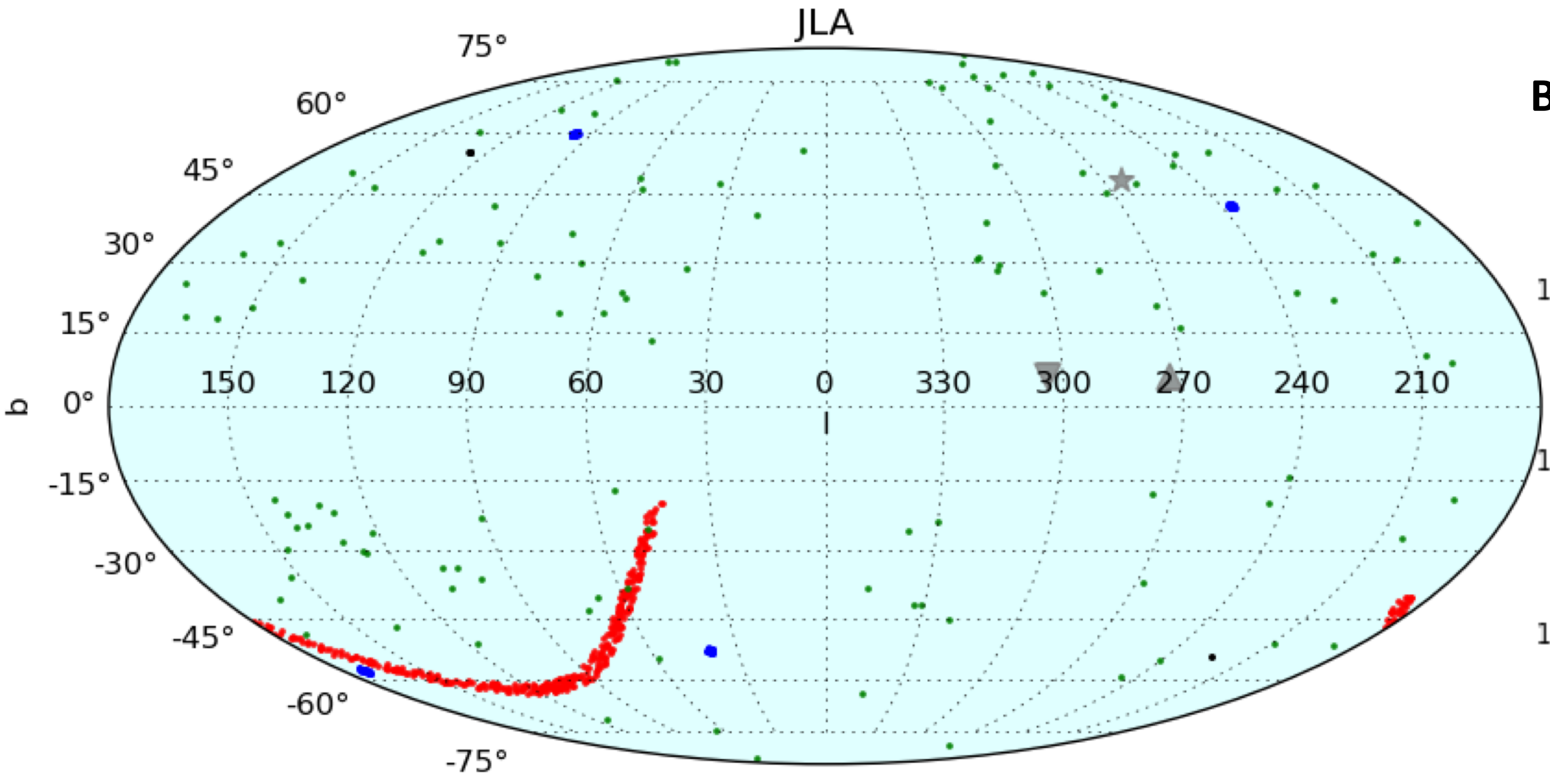
Perlmutter et al 1999 : The second most cited paper in all of physics

The data have intrinsic scatter:

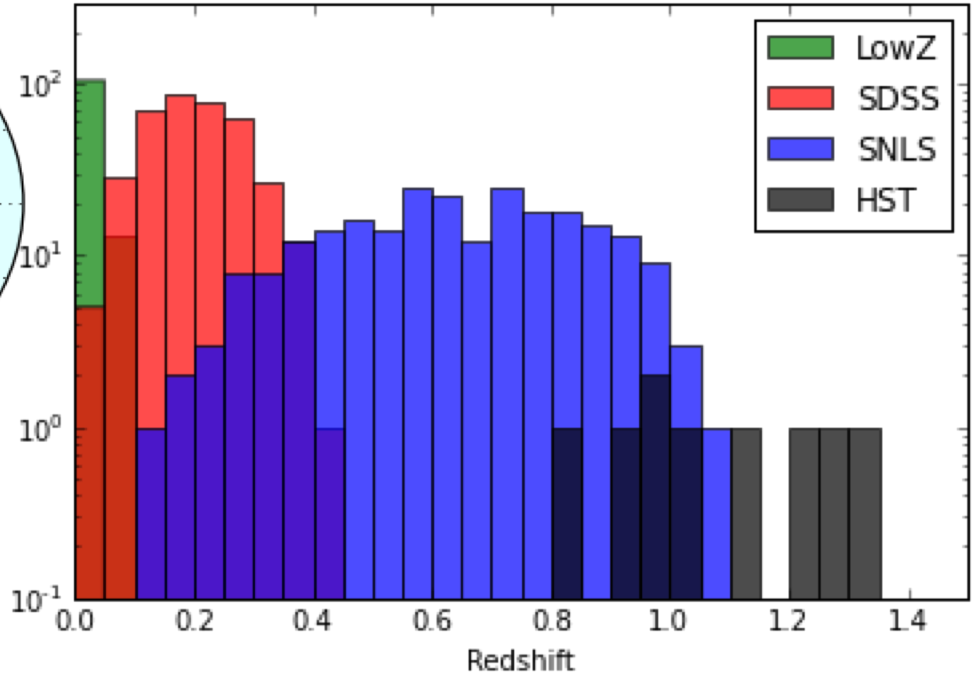
$$\chi^2_\mu = \Sigma \frac{(\mu_i - \mu_{obs})^2}{\left(\sigma^{fit}_{\mu,i}\right)^2 + \left(\sigma^{z}_{\mu,i}\right)^2 + (\sigma^{int}_\mu)^2}$$

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

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)

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

B-band

SALT 2 parameters

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

Name	$z_{\rm cmb}$	$m_B^\star$	X_1	C	$M_{\rm stellar}$
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

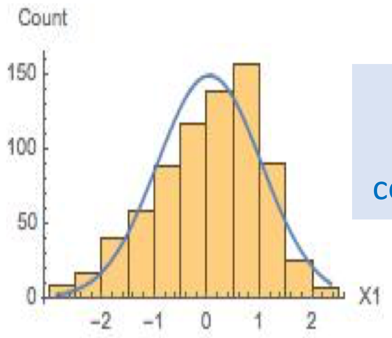
There may well be other variables that the magnitude correlates with …

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

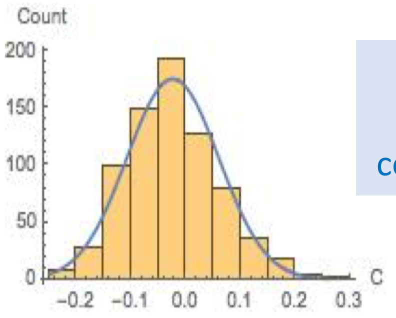
$$\mathcal{L} = \text{probability density}(\text{data}|\text{model})$$

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

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

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}

Confidence regions

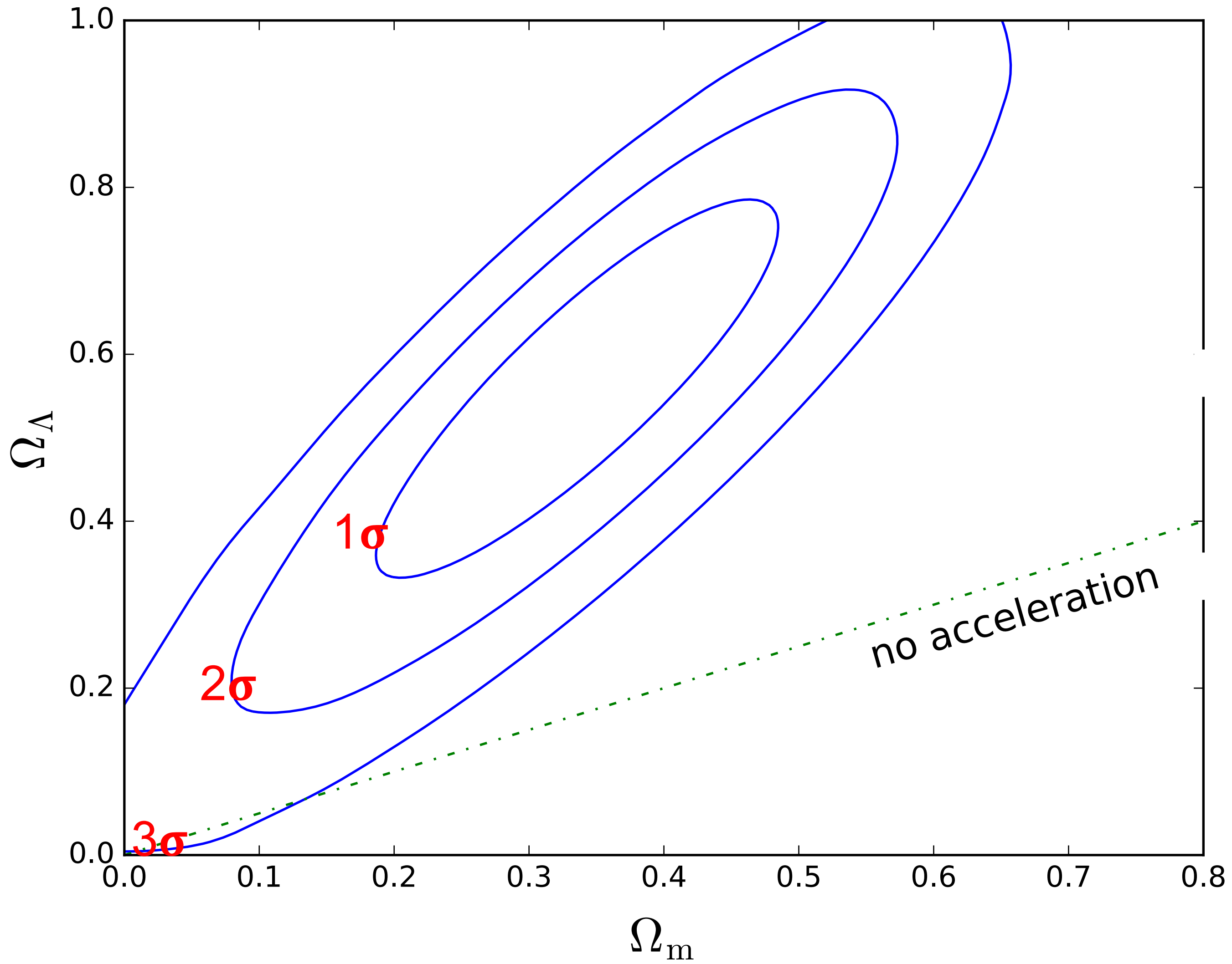
$$p_{\mathrm{cov}} = \int_0^{-2\log\mathcal{L}/\mathcal{L}_{\max}} \chi^2(x;\nu)dx$$

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

1,2,3-sigma

solve for Likelihood value

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

Peculiar velocity impact on SN1a magnitude

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

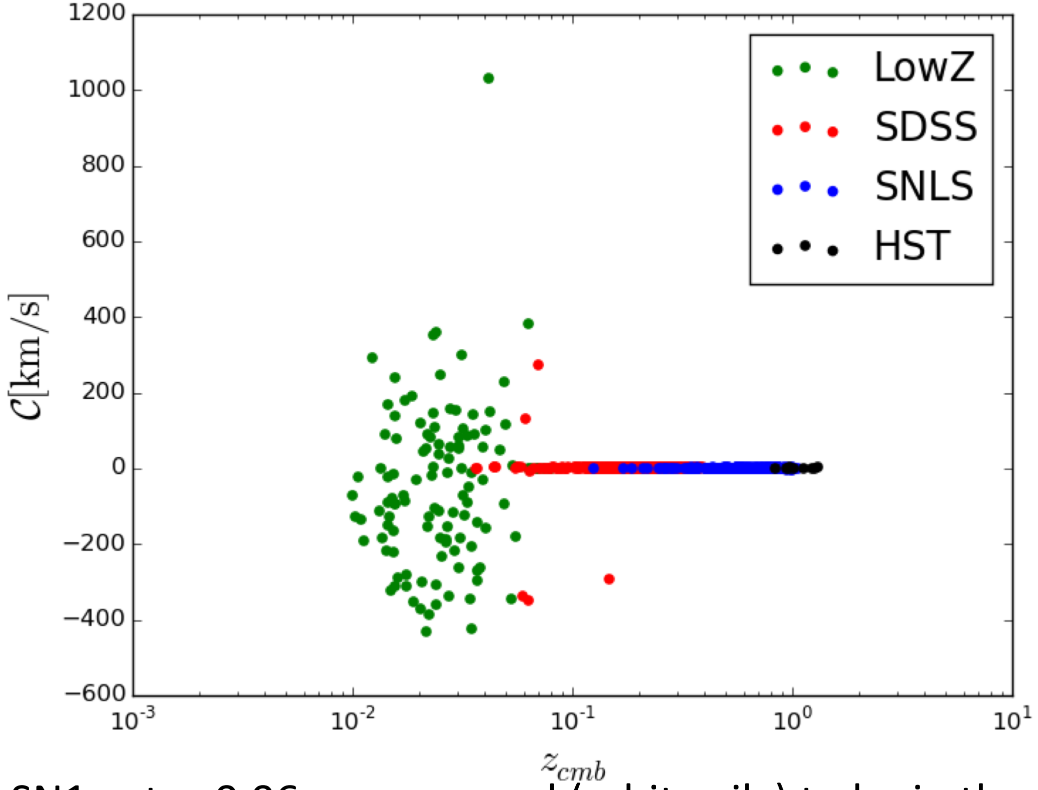
Davis et. al. Astrophys.J. 741 (2011) 67

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)
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

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

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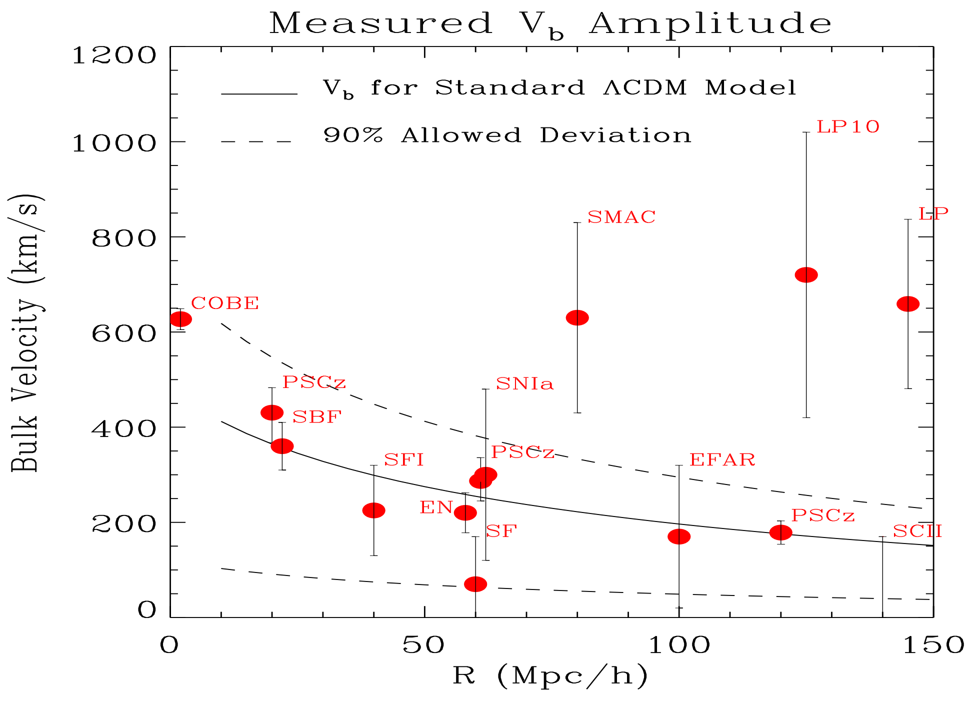

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Davis et. al. Astrophys.J. 741 (2011) 67

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```
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03D1aw 0.580724 0.582000 0 23.573937 0.090132
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```

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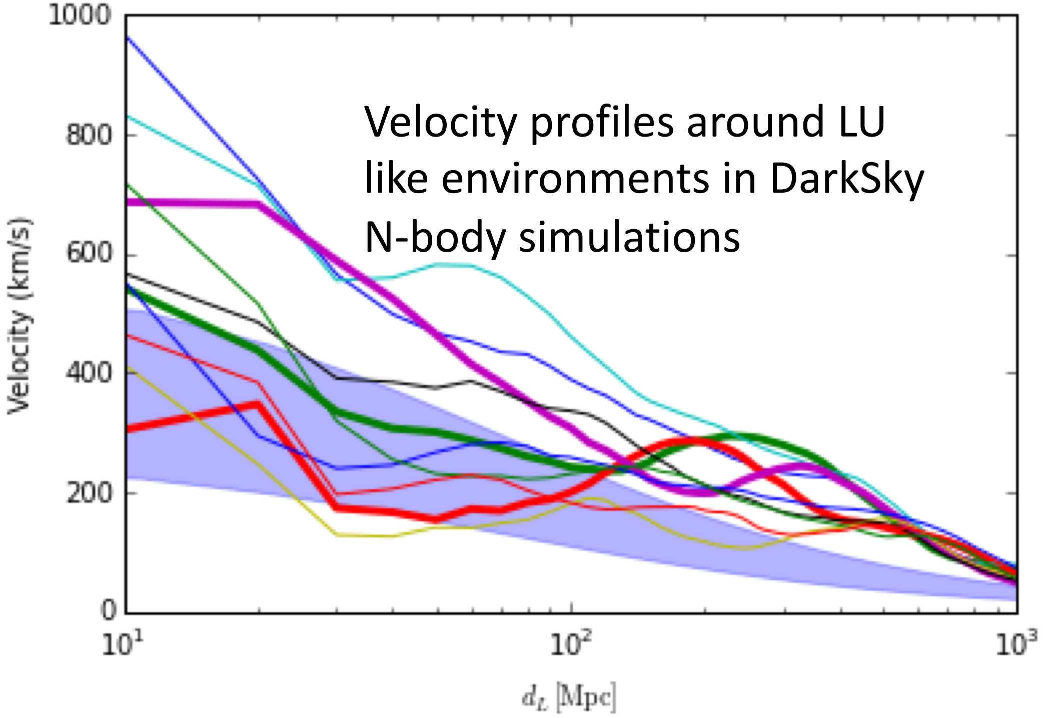

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The FLRW Universe in Kinematics

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

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

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

Matt Visser 2004

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

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 ($q_\mathrm{d}=0$)	−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. ($q_\mathrm{m}=0$)	−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}]
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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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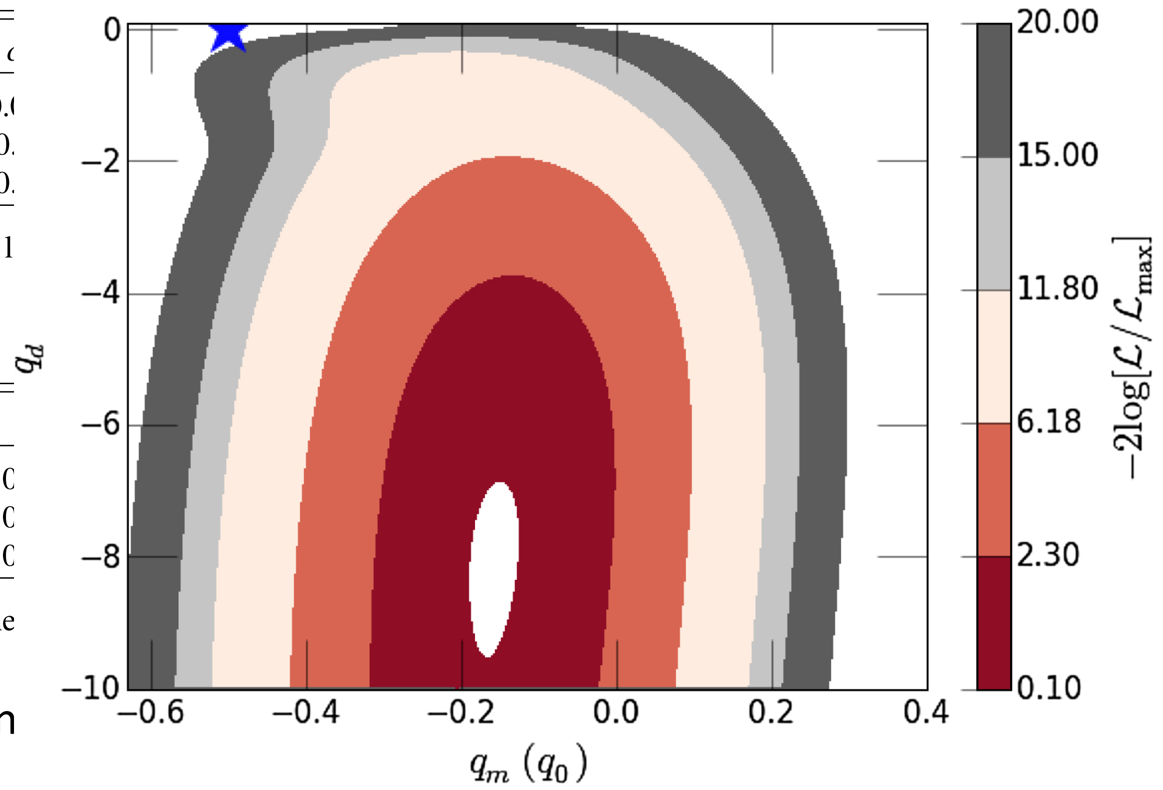
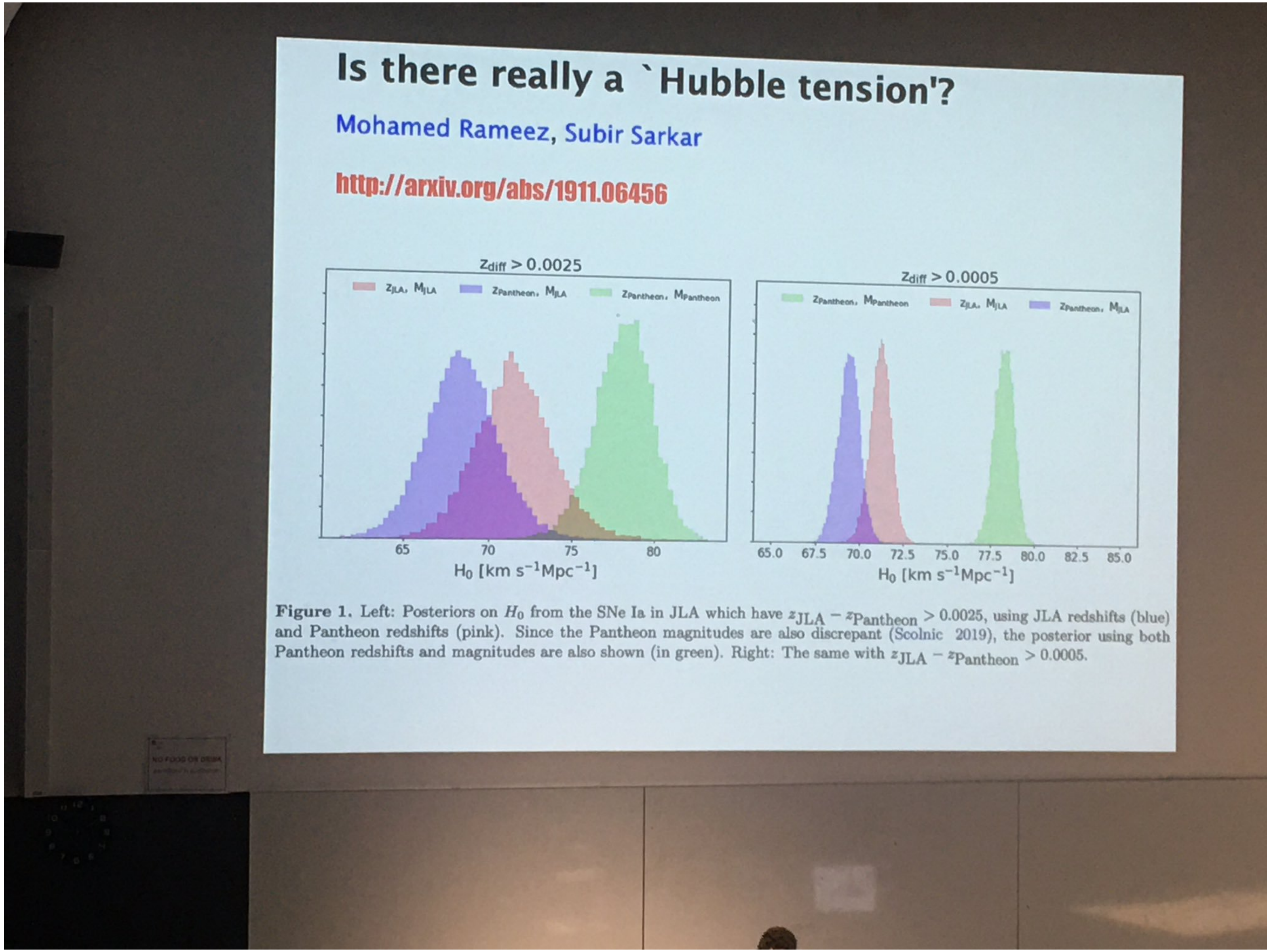
Notes. The BIC for the models above is −131.01, −130.55, and −135.46, providing positive evidence for the

The dipolar component of q is larger than the monopole, and domin

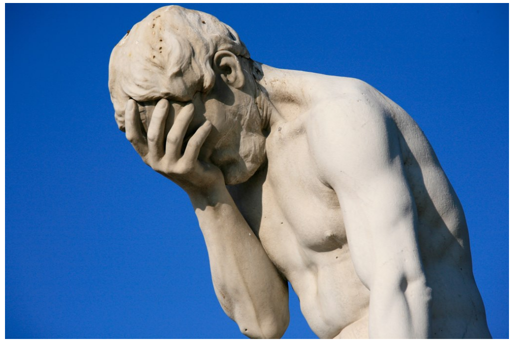


The significance of q_o being negative is $<1.4\sigma$!

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



This was discussed in the TeVPA opening plenary today in Sydney, by Celine Boehm



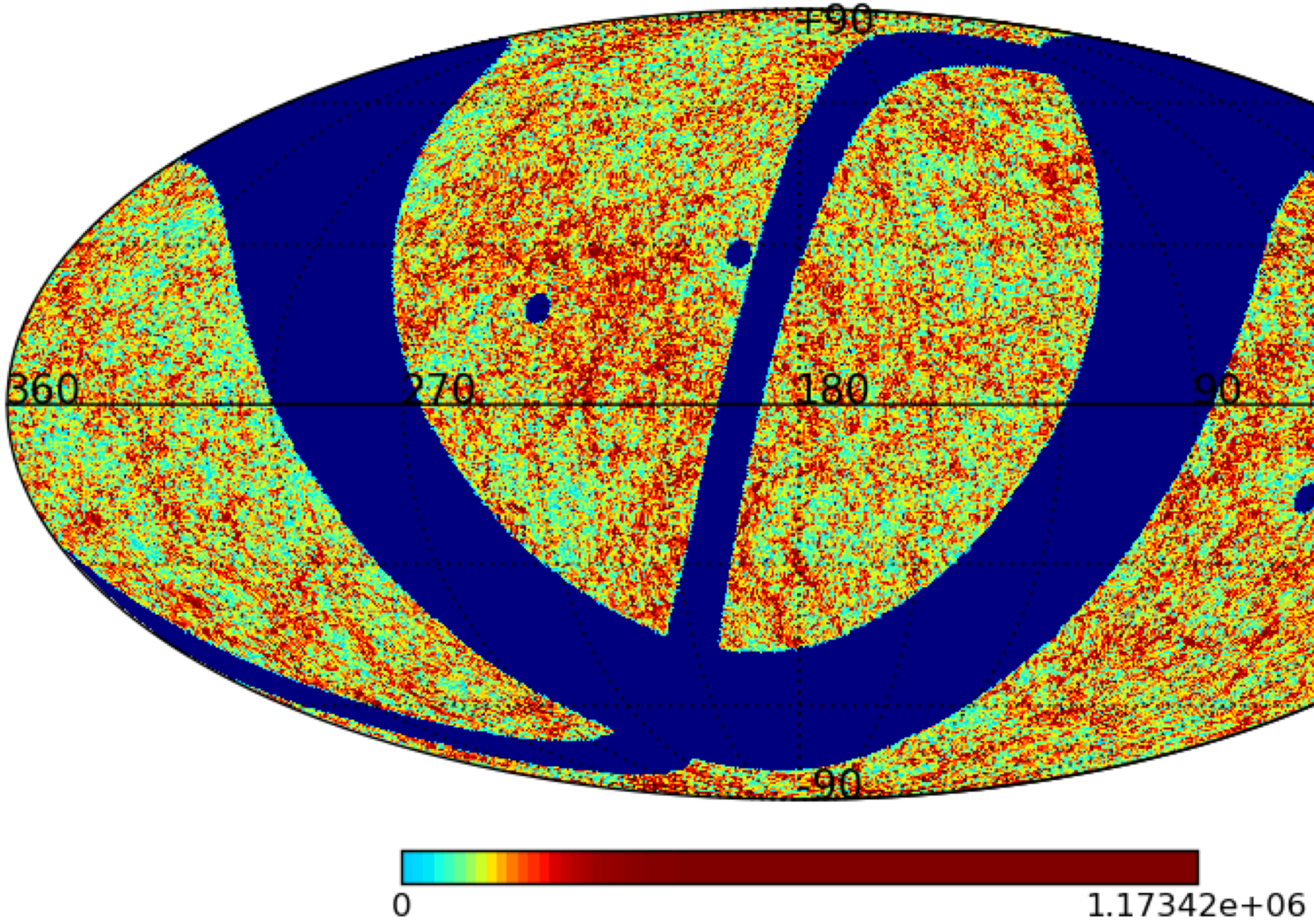
https://twitter.com/higgsinocat/status/1201263556978589696

On the measurement of cosmological parameters

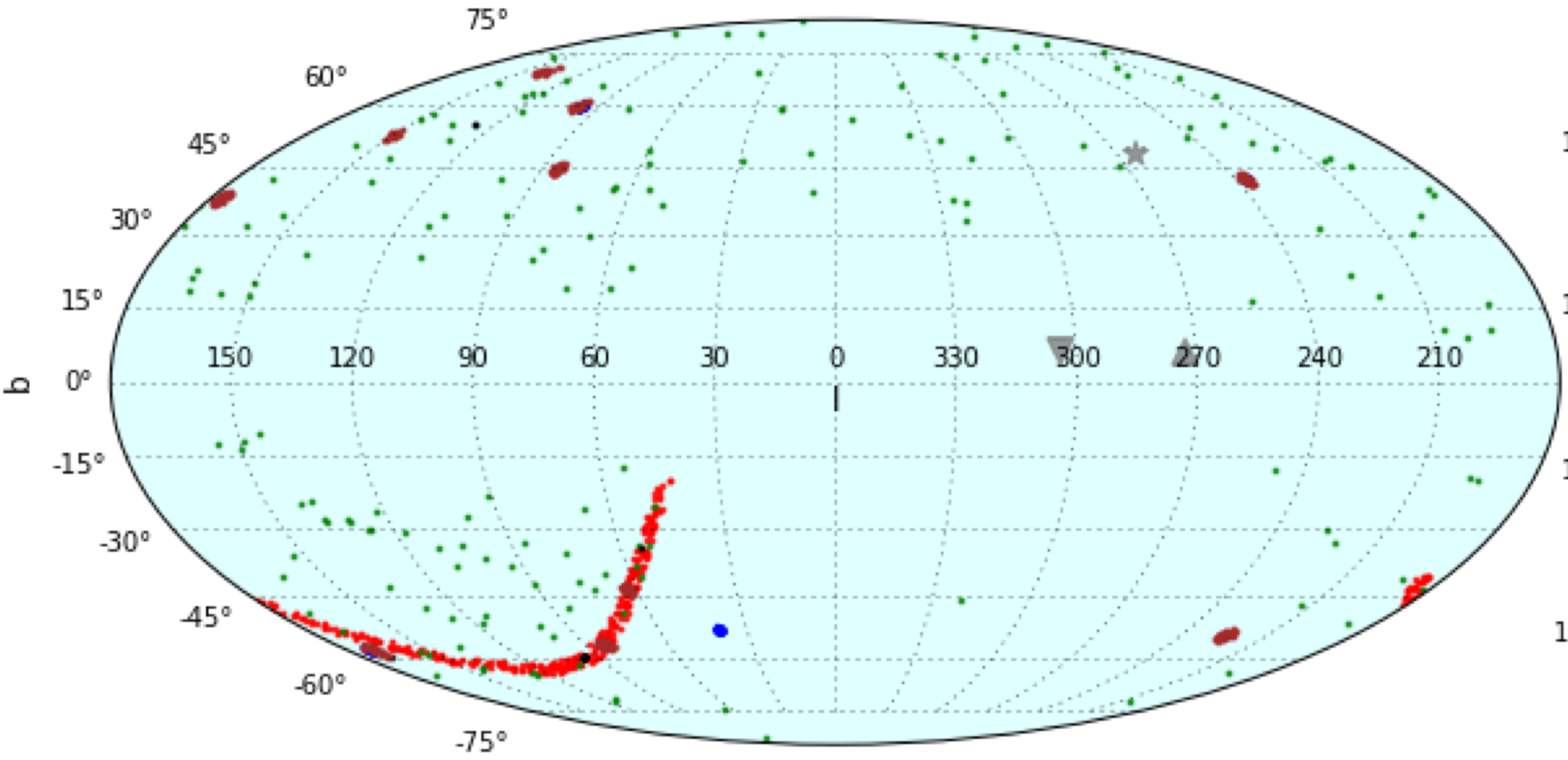
Rupert A. C. Croft, Matthew Dailey (CMU)

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

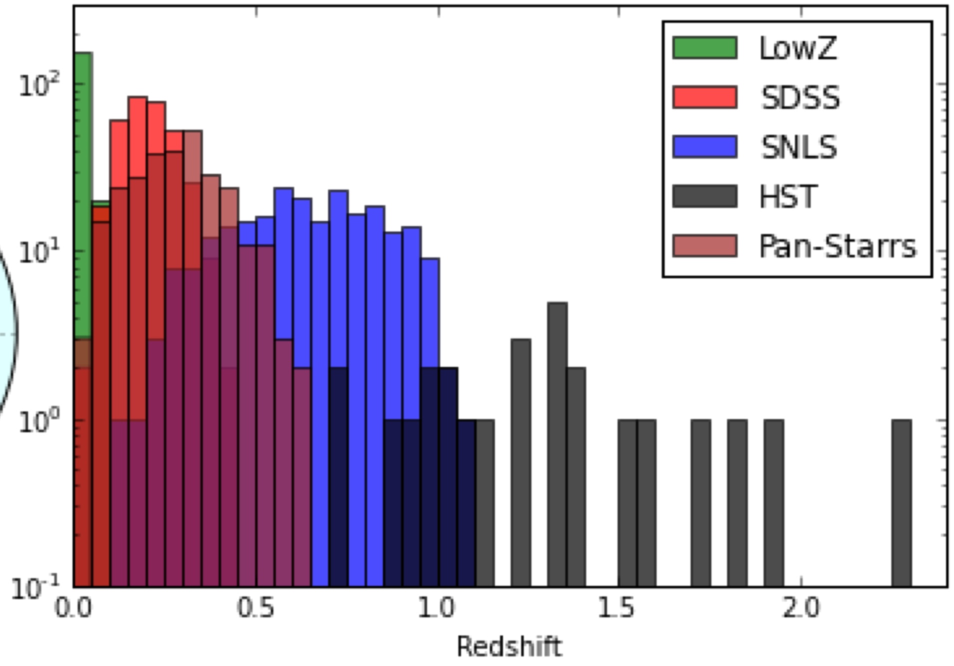
We have catalogued and analysed cosmological parameter determinations and their error bars published between the years 1990 and 2010. Our study focuses on the number of measurements, their precision and their accuracy. The accuracy of past measurements is gauged by comparison with the WMAP7 results.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



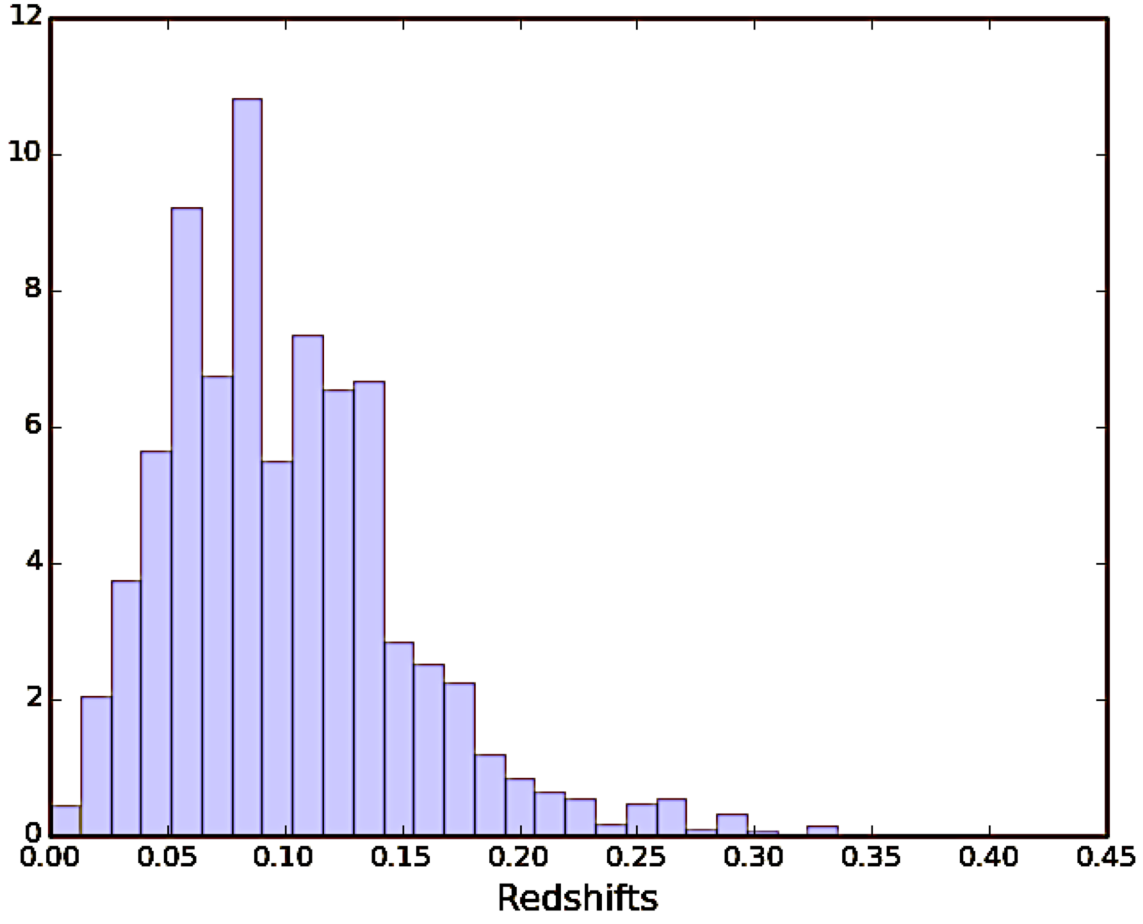
Scolnic et al. Astrophys.J. 859 (2018) no.2, 101



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!

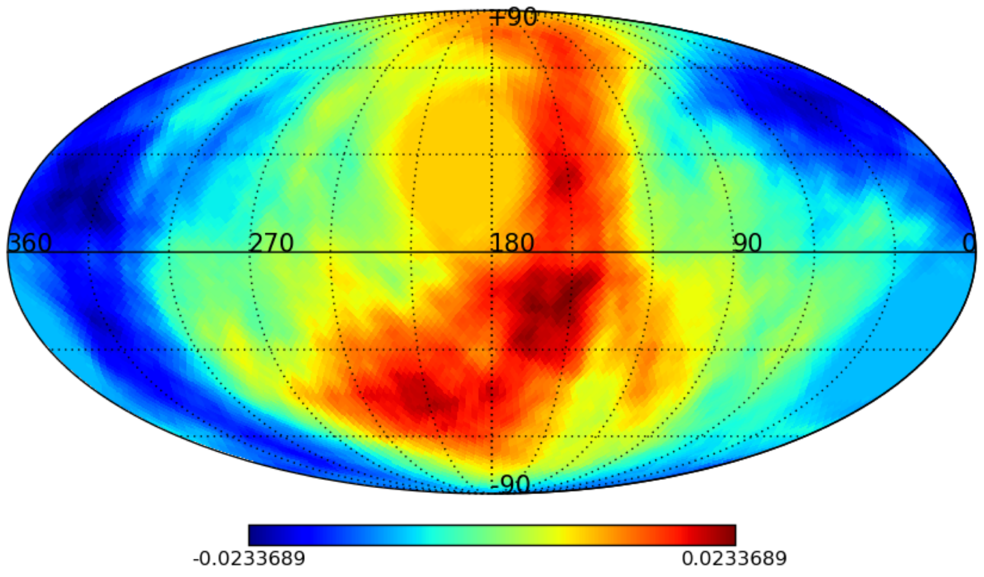
Redshift distribution of the removed sources



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)

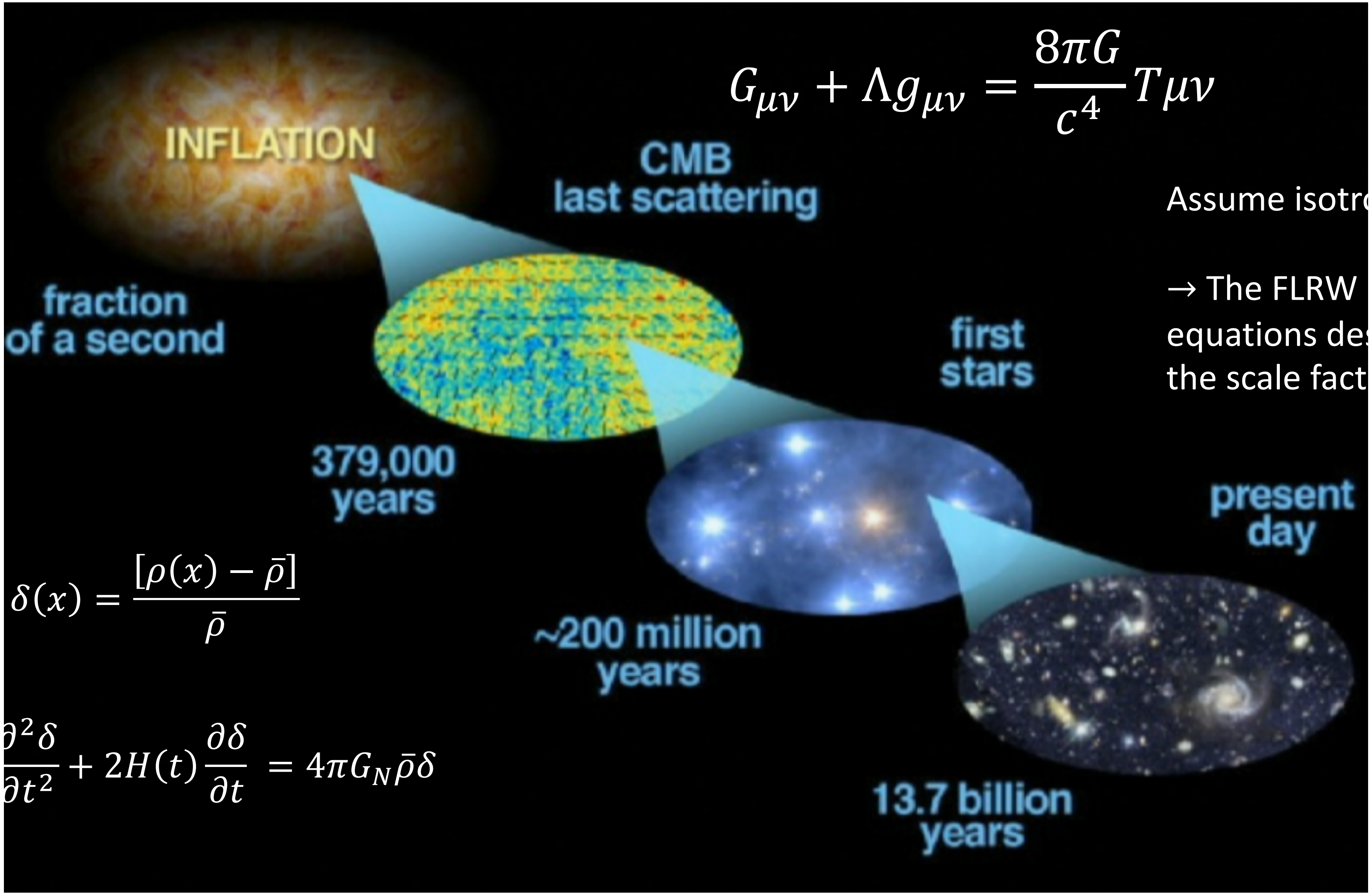
Total dipole is at least 4.2σ statistically significant.



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

Assume isotr

→ The FLRW
equations des
the scale fact



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

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

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

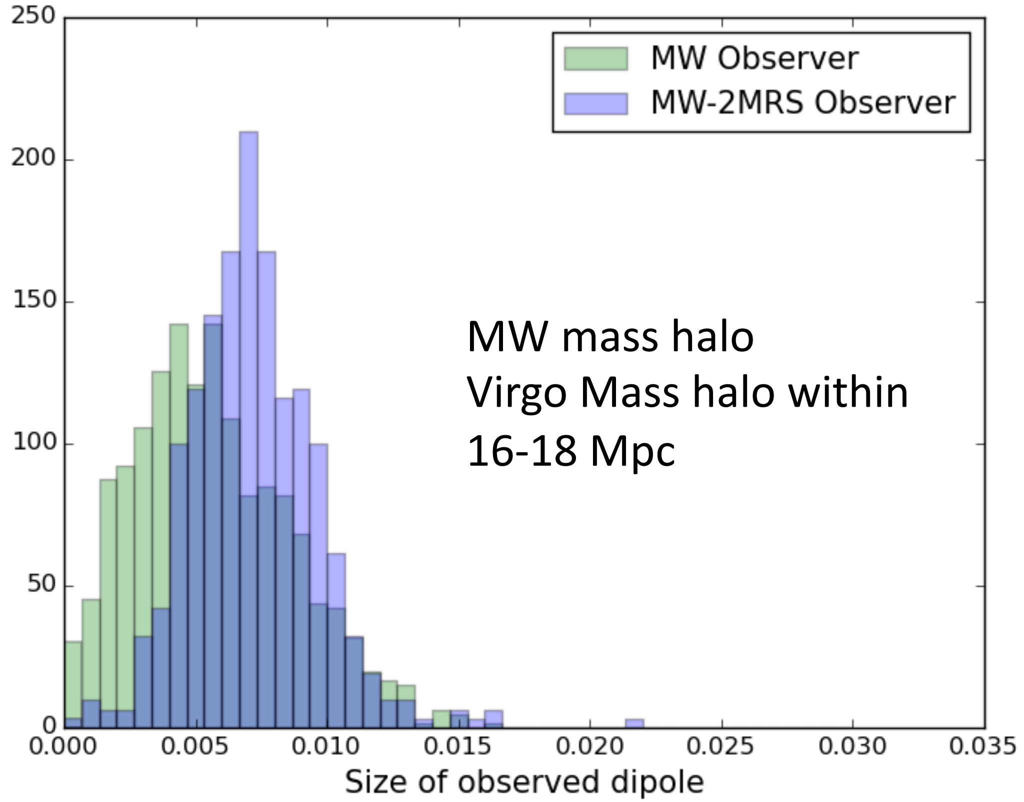
$\langle D_{cls} \rangle$ < 0.0018
In the final sample

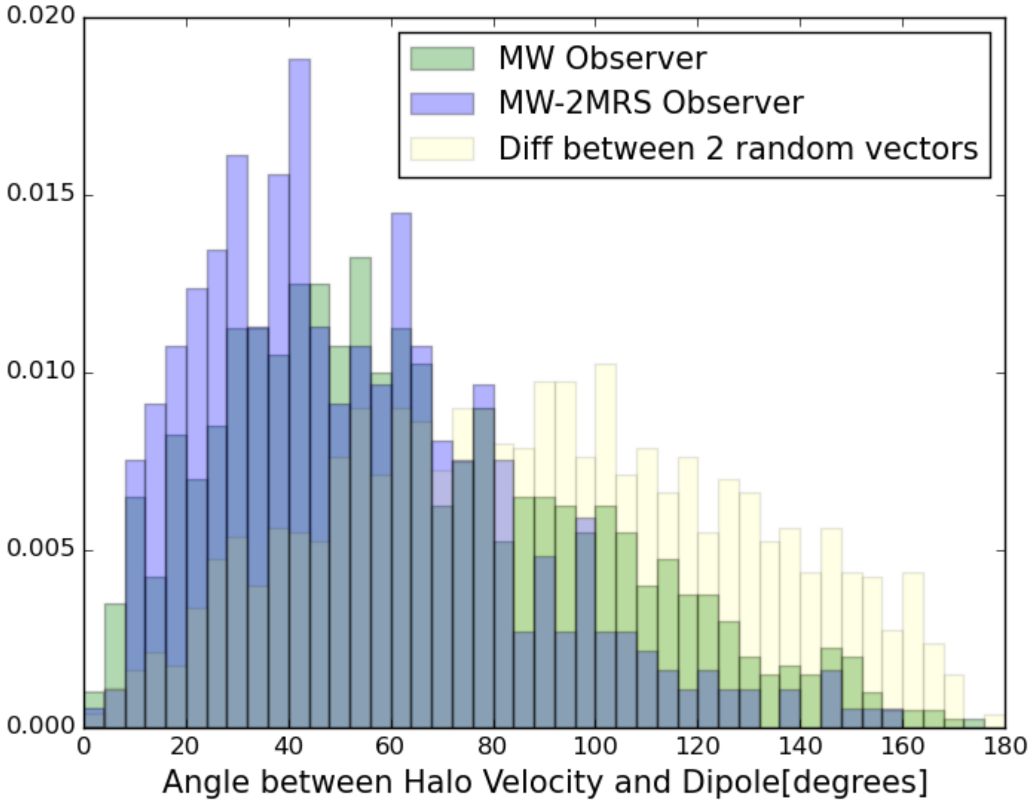
$D_{kin} = 0.0106$

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

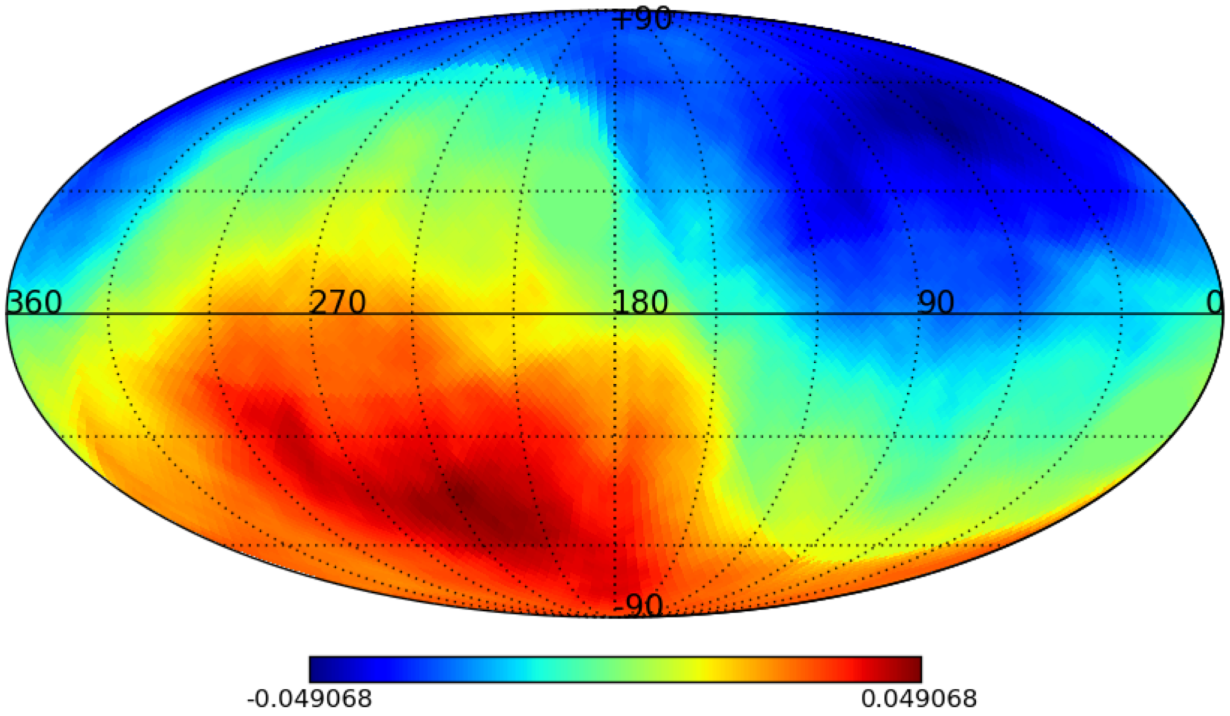
$\langle D_{cls} \rangle$ = 0.0076 +/- 0.0022

$\langle D_{kin} \rangle$ = 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

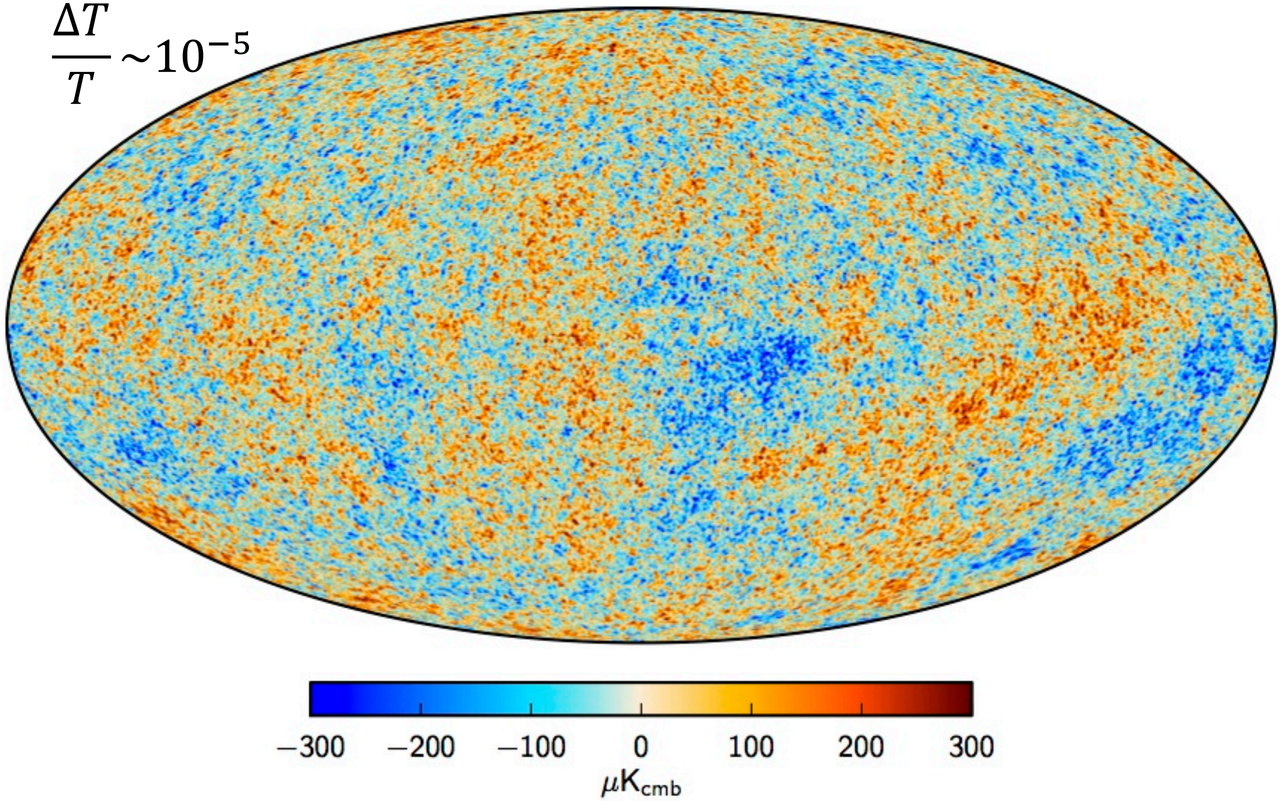
Fully kinematic interpretation ~ 6000 km/s

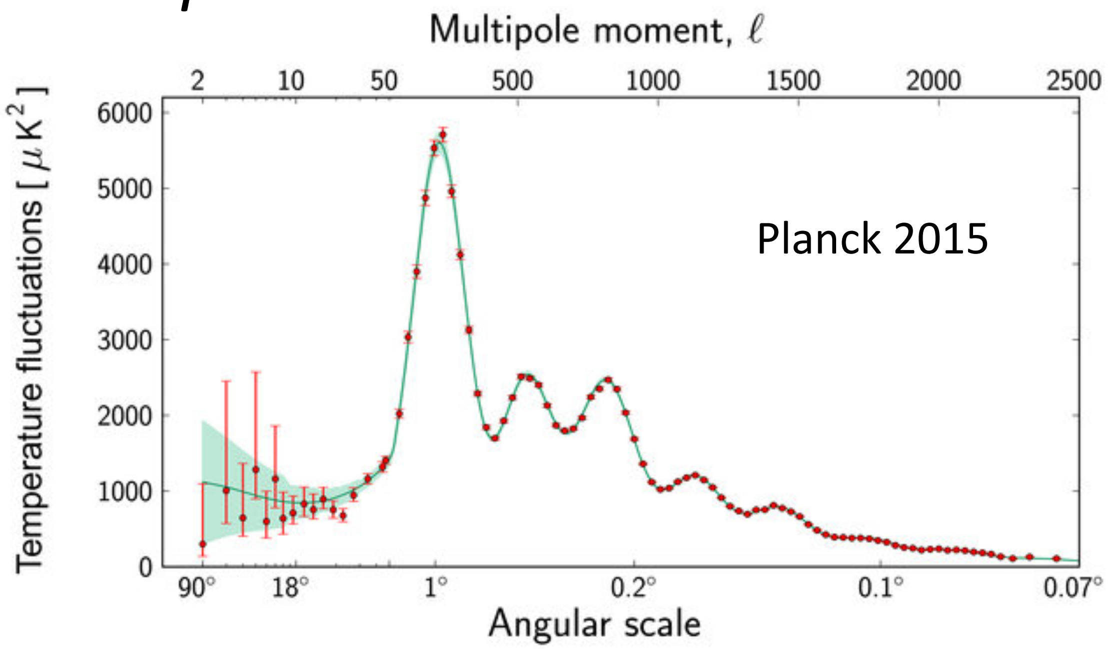
in agreement with MNRAS 445 (2014) L60-L64

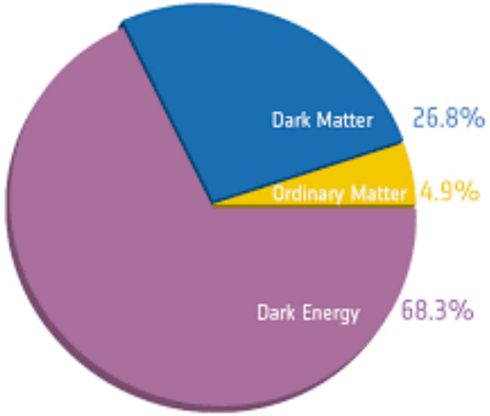
"Data from the Planck satellite show the universe to be highly isotropic"

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)